Train movement under the virtual coupling system: the VCS applications used to increase route capacity and to reduce delay

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The candidate confirms that the work submitted is her own. The contributions of the candidate to this work have been explicitly indicated below. In addition, the candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

The Virtual Coupling System (VCS) has been proposed as a new system for controlling trains by building groups of trains into train convoys. The main purpose is to increase route capacity by reducing separation distance between successive trains. This is achieved because successive trains under the VCS are separated only by a relative braking distance; this is much shorter than the separation distance required in the existing Fixed Block Signaling (FBS) and Moving Block Signaling systems (MBS). To achieve high capacity from the VCS, 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 velocity for maintaining the distance between them.

To date, many approaches have been introduced for controlling trains under the VCS. These approaches can be applied to control trains operating as a train convoy, in which a following train will operate depending on its leading train's movement. However, they might result in some shortcomings such as lower capacity due to exceeding separation distance, or unsafe and unstable movement that will limit the benefit from the VCS.

In this thesis, we propose an approach based on distance and velocity difference control laws and introduce the multiple state movements for simulating train movements under the VCS. The simulated results show that the route capacity is significantly increased compared to the capacity under the MBS. The separation distance between trains when they are in the convoy state is close to the required minimum safe distance under the VCS and obviously shorter than the minimum separation distance required when proceeding under the MBS. This also ensures that trains proceed safely in that the separation distance is greater than the minimum safe distance throughout the operation time period. We also show that trains can proceed smoothly, with a following train catching up with its leading train and joining up into the convoy with stable movement. In addition, the simulated acceleration and deceleration profiles show that they are limited within the realistic range.

One problem of the VCS is the loss of capacity when trains pass a junction. Various approaches have been introduced to control trains passing through a junction, but results show that the capacity at a junction is not significantly higher than capacity under the MBS. In this thesis, we also introduce the state movement controlling a train convoy passing over a junction. The simulated result shows that the capacity at a converging junction is increased as trains can operate as a train convoy passing through the junction. This could ensure that trains could operate safely, in which the distance between trains could be extended to at least minimum safe distance required at a diverging junction when they pass the junction.

The separation distance between trains under the VCS relies on many parameters such as operating velocity, braking rate, and velocity difference when building a train convoy. So, building a train convoy with different values may result different rates of capacity. 16 parameters that may impact on route capacity are determined. The capacity utilization in terms of number of trains, velocity deviation, timetable heterogeneity, and punctuality (travel time) is also determined for identifying how a parameter impacts on route capacity. According to the simulated results, it is found that building trains into a convoy and transferring them into the convoy state earlier will increase route capacity. There are many solutions such as using a higher velocity difference to build a train convoy, braking by using a higher braking rate, etc.

Building trains as a train convoy could not increase route capacity if the number of trains that could proceed along the same route is lower than the maximum number of trains under the MBS. So, the VCS should be used when the number of trains that will proceed along the same route is over capacity under the current signalling system. As we know the number of trains, we could use the VCS approach to create a new timetable. The idea is to merge some trains into a train convoy in order to lengthen the time gap in front of/behind a convoy sufficiently to insert an extra train. In this thesis, the proposed VCS approach is used to manage train timetable. By following this approach, we can identify which trains should be merged as a train convoy, how many trains will be built into the same convoy, and how they are merged into a train convoy. Simulation results show that the time gap in front of and/or behind a train convoy is increased sufficiently to allow an extra train to be inserted safely. Thus, the route capacity in terms of the number of trains could be increased compared to maximum capacity under the MBS.

In operating state, a train may be delayed reducing route capacity. In this thesis, we propose the VCS approach to build a delayed train and an impacted train (a train that will decelerate causing delay due to the delay of its front train) together as a train convoy. This will allow an impacted train to proceed with constant velocity until the distance separated from a delayed train is shorter than relative braking distance. So, delay could be prevented or delayed. The simulated results show that secondary delay could be reduced, and it is significantly lower than delay when trains operate under the MBS.

List of Abbreviations

ATP	**A**utomatic **T**rain **P**rotection
CC	**C**apacity **C**onsumption (%)
EMH	**E**ast **M**idlands **H**ub
EoA	**E**nd of **A**uthority
ERTMS	**E**uropean **R**ailway **T**raffic **M**anagement **S**ystem
ETCS	**E**uropean **T**rain **C**ontrol **S**ystem
FBS	**F**ixed **B**lock **S**ignalling
HET	**Het**erogeneity
MA	**M**ovement **A**uthority
MBS	**M**oving **B**lock **S**ignalling
RBC	**R**adio **B**lock **C**entre
SAHR	**S**um of **A**rrival **H**eadway time **R**eciprocals
SM	**S**afety **M**argin
SSHR	**S**um of **S**hortest **H**eadway time **R**eciprocals
SvL	**S**upervised **L**ocation
VCS	**V**irtual **C**oupling **S**ystem
V2I	**V**ehicle to **I**nfrastructure
V2V	**V**ehicle to **V**ehicle

Notations

$\Delta x_k(t)$	Separation distance between a leading train (k) and a following train k+1 at time t.
$\Delta x_k^{min}(t)$	Minimum safe distance between successive trains
$\Delta x_k^{smin}(t)$	Modified minimum safe distance between successive trains
Δx_k^{mdvr}	Minimum safe distance at a diverging junction
Δx_k^{mcvr}	Minimum safe distance at a converging junction
Δt	Time step (time for commination, and update the position and speed of a train)
v^{max}	Velocity limit along the route
v^{maxp}	Velocity limit restricted at a junction
$v_k(t)$	Velocity of a train at time t
x_{k+1}^{opb}	Optimal braking point (the point that a should start decelerating for transferred into the convoy state)
a_k^{max}	Maximum acceleration rate
a_k^{opt}	Optimal acceleration rate
b_k^{max}	Maximum deceleration rate
b_{k+1}^{vcs}	Maximum braking rate that a following train can apply for braking
b_k^{opt}	Optimal acceleration rate
l_k	Train length
Δv_k^{mer}	Merging velocity difference between successive trains
v_k^{mer}	Merging velocity of a train
T^{pnt}	Turnout switch operation time
SM	Safety margin
C_{pln}^{max}	Maximum capacity for plain route
C_{cvr}^{max}	Maximum capacity at a converging junction
C_{dvr}^{max}	Maximum capacity at a diverging junction
Δx_k^{exd}	Required extended distance between successive trains
Δv_k^{spt}	Splitting velocity difference between successive trains
v_k^{spt}	Splitting velocity of a train

Δt_{k+1}^{cst}	Total time that a following train has split from a convoy
v_{k+1}^{idl}	Ideal velocity (optimal velocity based on timetable)
Δx_{k}^{dec}	Different travelling distance while a following train decelerating from current velocity to its splitting velocity
Δx_{k}^{cst}	Different travelling distance between successive trains during splitting state
Δx_{k+1}^{spt}	Length of splitting zone (from an optimal splitting point to the beginning of safe zone)
T^{ecv}	Estimated reaching time (estimated time that a train reaches a converging junction)
ΔT^{ecv}	Estimated reaching time difference between an inserted train and a train on the main route.
ΔT^{min}	Minimum headway time for plain route
ΔT^{mcvr}	Minimum headway time at a converging junction
ΔT^{ext}	Required extra time gap.
ΔT^{est}	Estimated extended time gap.
Δx^{ext}	Required extra distance.
Δx^{mer}	Merging distance (distance from an optimal merging point to the beginning of safe zone).
x^{mer}	Merging starting point (The point that a train start adjusting velocity for merged a convoy).
Δt^{mer}	Total time for extending time gap from current to required time gap
Δv^{omer}	Optimal merging velocity difference between two successive trains
K	Involved trains (trains that their headway time away from an inserted train is lower than the minimum safe headway).
N	Number of trains in a convoy.
ΔT_{Lead}^{etg}	Estimated extended time gap obtained after building a leading convoy
Δt_{Lead}^{rst}	Residual time gap from the leading convoy

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Chapter 1
Introduction

1.1 Background

In 2020, the number of passenger journeys by rail in the United Kingdom was about 1,742 million, an increase of approximately 30% compared to the journey numbers recorded in 2010 (ORR, 2020b). To cater for this large increase in passenger demand, the number of train services needs to be increased. Expanding routes or constructing new routes are possible solutions to solve the problem but there are many problems with these, including unavailability of investment funds and limitations on an available space.

Adding more trains operating on the existing route could be considered as an alternative solution. However, on routes where the percentage of capacity consumption is close to the maximum capacity, in that the separation distance between any successive trains (the distance from the rear of a leading train to the head of a following train) is close to the minimum safe distance, more trains could not be added. Adding more trains might impact badly on the effectiveness of train operation, in which the number of cancelled and significant delayed trains might be increased. According to the delay data reported by Network Rail between 2015 and 2020, the number of cancelled and significant delayed trains (more than 30 min delay) had increased especially on the busy routes. One important cause of delay is due to the increase in the number of trains operating on the same route (ORR, 2020a). To increase route capacity, trains need to operate closer each other. So, the separation distance between trains should be reduced allowing more trains to operate along the same route. This challenge has been studied by many railway programs such as European Shift2Rail programme (Goverde, 2020), and the Digital Railway Programme (NetworkRail, 2021). The main purpose is to introduce a more effective signalling system and technology to increase route capacity by reducing the separation distance between trains.

Currently, the signalling system adopted across the whole UK rail network is mostly the Fixed Block Signalling (FBS) which uses trackside signals to inform the status of the next block section. Necessary information such as next block signal status, estimated velocity curve, etc. is provided in the train cab (NetworkRail, 2018). The successive trains are separated by the block length which depends on the highest velocity of trains operating on the route. Based on the condition that only one train can occupy each block at any one time, the separation distance between successive trains is fixed and might be higher than the necessary distance to stop a train safety (longer than absolute braking distance). To increase capacity of the existing route, the signalling system named “Moving Block Signalling” (MBS) is introduced. The main idea is to allow a following train to be separated from its leading train by at least the absolute braking distance. The current velocity and positions of all trains within the control area are detected and sent to the control centre to calculate movement authority to be sent back to a train. The optimal velocity curve is created relying on the next braking point (the object in front or the rear of its leading train). A train will proceed following the ideal velocity curve to ensure that the distance in front is long enough for stopping before reaching the next braking point. This could ensure that a following train could stop safely avoiding collision and the route capacity could be increased compared to the capacity under the FBS.

On a high-speed route where a train’s velocity could be higher than 300 km/h, its absolute braking distance is very long as a train might need longer than 10 km for stopping. So, the route capacity obtained from the MBS and FBS might not be different. Based on the fact that a train will not stop dead after applying the brakes, the sufficient distance between successive trains could be decreased. It will be shorter than the absolute braking distance required for separating a couple of trains when proceeding under the MBS.

Currently, a new signalling control called “Virtual Coupling System (VCS)” is being proposed mainly for increasing route capacity by reducing distance between trains. It has been developed for potential use in the real operations. The minimum separation distance required for the system is only the relative braking distance which is shorter compared to the separation distance under both FBS and MBS. This distance relies on the relative operating velocity of a train and its front train and the maximum braking rate of a train. Using the benefit from such a shorter distance between trains, a higher number of trains could operate increasing route capacity. The challenge is to operate a train following each other by maintaining safe distance from a train ahead. There are many approaches introduced for simulating trains operating under the VCS. However, they have some limitations such as unsafe movement, unstable travelling, etc. In addition, there is no clear statement identifying when the VCS should be used.

1.2 Problem statements, objectives, and related tasks

Many approaches have been proposed for building a group of trains as a train convoy. The results have proved that the distance between trains is decreased, possibly so that more trains can be added into the same route. However, there are some limitations that should be eliminated in order to control trains operating as a train convoy more effectively. The section below shows the list of problem statements that could occur when trains are operated under the VCS.

1.2.1 Are the previous approaches effective to simulate trains operating under the VCS?

1.2.1.1 Problem statement

It is well known that the route capacity under the VCS is theoretically higher than capacity under other signalling controls. The separation distance between trains is reduced to just a relative braking distance that will allow more trains to operate along the same route. Currently, many approaches have been proposed for simulating trains proceeding under the VCS. However, there are some shortcomings that limit the benefits that could be obtained from the VCS. Some approaches result a longer separation distance than required. Some result in unsafe situations such that the separation distance between trains may be shorter than the relative braking distance. Another obvious shortcoming is unstable travelling, in which a following train adjusts its velocity frequently in order to merge itself into a train convoy

1.2.1.2 Objective

The objective of this part is to propose an approach for controlling trains under the VCS more effectively. The separation distance between trains should be close to, but not shorter than the relative braking distance to ensure that trains can operate safely, and the route capacity can be increased. In addition, a train can obtain stable travelling, in which it should operate by constant velocity to be merged into a train convoy.

1.2.1.3 Related tasks

To create an effective approach for controlling trains under the VCS, there are four related tasks including:

(1) Modifying the minimum safe distance equation: An additional term is added into the traditional relative braking distance equation for improving safety.

(2) Introducing the conditions and state movement for controlling trains operating under the VCS: The approach is developed based on the distance and velocity difference control laws.
(3) Providing the equations to calculate acceleration and deceleration rate:
(4) Determining the effectiveness of the proposed approach (**Chapter 4**)

1.2.2 How a train convoy operates when passing a junction?

1.2.2.1 Problem statement

When a train convoy is approaching a diverging junction where successive trains may diverge continuing on different routes, a following train will normally be forced to operate by a lower velocity than its leading train for extending the separation distance between them. Various approaches have been suggested to control a train convoy passing a junction. Some approaches result unsafe situation, in which the distance when passing a junction is shorter than minimum safe distance. Some of them could not be used well in the case that there are more than two trains in the same convoy.

1.2.2.2 Objective

The aim of this part is to propose the approach to control trains passing a junction safely and aim to prove that using the VCS could increase route capacity even though a train convoy passes a junction.

1.2.2.3 Related tasks

The related tasks include:

(1) Introducing the optimal splitting point (the point that a following train should start splitting for obtaining safe distance from its leading train).
(2) Proposing the state movement that could be used to control trains passing through a junction safely.
(3) Determining the effectiveness of the proposed state movement (**Chapter 4**).

1.2.3 Could trains be coupled more effectively?

1.2.3.1 Problem statement

The separation distance between train might be different if a train convoy is built by using different values of some parameters such as braking rate, operating velocity, etc. Thus, the distance between trains could be different causing different route capacity.

1.2.3.2 Objective

When trains operate under the VCS, many parameters will impact on route capacity. In this part, the objective of this part is to determine whether a parameter impacts route capacity and to identify how it impacts route capacity. The outcome could be used as a guideline for building a train convoy.

1.2.3.3 Related tasks

There are two related tasks below.

(1) Calculating the percentage of capacity consumption of each value and comparing them to determine whether it impacts on capacity.
(2) Calculating capacity utilisation (number of trains, velocity deviation rate, the rate of timetable heterogeneity, and punctuality) to determine why the percentage of capacity consumption is different.

The simulated results of each parameter and the evaluation of whether and how it impacts route capacity are shown in the **Chapter 5**.

1.2.4 When the VCS should be applied?

1.2.4.1 Problem statement

From previous studies, it is not clear exactly when trains should be coupled into a train convoy (when the VCS should be used). Quaglietta & Goverde (2019a) suggest that the VCS should be applied when the separation distance between successive trains is shorter than the absolute braking distance But building a train convoy may not help to increase route capacity if the number of trains that can operate along the same route is still lower than maximum capacity under the main signaling control. Building a train convoy may increase travel time especially a leading train that will operate by a lower velocity than its following train in order to allow a following train to catch up with it.

1.2.4.2 Objective

The objective of this part is to introduce a flowchart based on the VCS to create a new timetable in the case that the number of trains that will operate along the same route is higher than capacity under the MBS. A new timetable will show which trains should be merged into a train convoy, how many trains should be in a convoy, and how trains are merged into a train convoy.

1.2.4.3 Related tasks

The main task is to propose a flowchart based on the VCS concept to determine the sub-tasks below.

(1) Identifying which train should be merged into a train convoy.
(2) Considering how many trains should be built into the same convoy.
(3) Proposing the equation used to calculate the optimal merging velocity for an involved train (a train that will be merged into a train convoy).
(4) Determining the effectiveness of the proposed approach.

The creation of a new timetable based on the VCS is shown in **Chapter 6**. It is noted that trains will operate based on the proposed state movement in the **Section 3.2.1**.

In operating state, an involved train may be delayed and may not be merged into a train convoy by using a suggested merging velocity. The proposed flowchart can also be used in operating state to manage a train timetable to re-determine a set of involved trains, and to re-calculate the optimal merging velocity for an involved train. The simulated train movements based on a new timetable in operating state are shown in **Chapter 7**.

1.2.5 Any benefits could be obtained from the VCS?

1.2.5.1 Problem statement

Based on the fact that the separation distance between trains required at a diverging junction is normally longer than the distance required along plain route, a following train will be forced to operate with a lower velocity than a train ahead for lengthening the distance safely for passing through a junction. The deceleration of a train may force its following trains to decelerate causing delay. In addition, the minimum safe distance required at a junction is equal to the safe distance under the MBS. Thus, the capacity at a junction cannot be increased even though trains have operated under the VCS. At a diverging junction, some successive trains will continue on different routes, but some still proceed on the same route. To increase capacity and/or to reduce delay, trains that will proceed on the same route should be coupled as a train convoy passing through a junction.

In the case that a train is delayed, it will impact the movement of its following trains forcing them (impacted train) to decelerate causing delay as well. As the VCS requires a shorter separation distance, an impacted train can be merged into a train convoy with a delayed train in front to reduce delay.

1.2.5.2 Objectives

The main objective of this part is to reduce secondary delay. Using the benefit from the VCS, the secondary delay could be reduced by building any delayed trains with the impacted trains running behind together as a train convoy.

1.2.5.3 Related tasks

There are three related tasks below.

1. Proposing the flowchart (with a set of conditions) for creating a train convoy to reduce delay.
2. Proposing the flowchart (with a set of conditions) for creating a new trains convoy to reduce delay when trains are passing a diverging junction.
3. Determining the effectiveness of the proposed flowcharts by comparing delay with and without the VCS.

The **Chapter 7** shows the examples of simulated train movement based on the proposed flowchart.

1.2.6 Are the proposed approaches effective to operate trains under the VCS in both planning and operating state?

In the last chapter (**Chapter 8**), we will use the proposed equations, state movements and flowcharts to manage a timetable and to operate trains in two cases: trains operate on-time, some trains are delayed. The objective of this part is to determine the possibility to use the VCS on the real train operation in both planning and operational state. The simulated route capacity in terms of the number of trains and the secondary delay of trains after applying the VCS are compared to the case that trains operate under the MBS.

1.3 Thesis outline

In this thesis, there are nine chapters (**Figure 1.1**) including:

Chapter 1: Introduction, objectives, related tasks, thesis outline, methodological framework, and contributions.

Chapter 2: The concept and feasibility of VCS, minimum safe distance between trains, the previous approaches applied for controlling train under the VCS, and parameters affecting route capacity.

Chapter 3: The methodology used in this thesis includes:

- The approaches for controlling a group of trains operating under the VCS and the measurement used to determine an effectiveness of the proposed approach.
- The timetable compression method and the four aspects of capacity utilisation.

- The flowchart to create a new timetable for inserting an extra train. (It is used in the case that the number of trains is over the route capacity).
- The flowchart to build a delayed train and an impacted train as a train convoy to reduce delay.

Chapter 4: The chapter presents the simulated results of train movement under the proposed approach. Effectiveness of the proposed approach is evaluated by three aspects including capacity, safety, and stability.

Chapter 5: This chapter shows the simulated results of trains for different values of parameters that may impact on route capacity. This also shows the determination of whether and how a parameter impacts on route capacity.

Chapter 6: This chapter shows the example of creating a new timetable (managing a timetable) in the case that more trains will be operated along the same route. The trains operating based on a new timetable are simulated to determine the effectiveness of the proposed flowchart.

Chapter 7: This chapter introduces the VCS applications to operate trains in different situations (a train is delayed and a train convoy is approaching a junction). Train movements in each situation are simulated to determine whether the application can be used effectively.

Chapter 8: This chapter presents a case study of high-speed trains operating between East Midlands Hub and Yorkshire. The proposed approaches, flowcharts, and VCS application are used to create a new timetable, and to operate trains under the VCS. The route capacity under the proposed approach is compared to the capacity when operating under the MBS. In addition, the ability to reduce delay time is also determined.

Chapter 9: The main contributions of the thesis are discussed along with points of limitation. Moreover, the chapter also suggests future research that could improve the approach for controlling trains operating under the VCS.

1.4 Methodological framework

To eliminate such the shortcomings stated in the **Section 1.2**, the approach for controlling trains operating under the VCS is developed. The objectives are to control trains operating under the VCS more effectively (Obtaining a higher capacity than MBS, operating safely, and obtaining stable travelling). The approach is developed based on the distance and velocity difference control laws (**Section 3.2**), in that a following train's velocity will be adjusted depending on the separation distance and relative velocity compared to a train ahead. The state movement (merging, convoying, and splitting sate) is introduced to build a train convoy (**Section 3.2.1.1**), to control trains operating as a train convoy (**Section 3.2.1.2**), and to split a train from a convoy (**Section 3.2.1.3**) when passing a junction or approaching a station. To determine an effectiveness of the proposed approach, three aspects including capacity, safety, and stability are determined (**Section 3.2.3**).

To determine the impact of a parameter on route capacity, the percentage of capacity consumption of different values are compared. The percentage of capacity consumption is measured using the timetable compression method (UIC 406 code in the **Section 3.3.1**). The capacity utilisation in terms of number of trains, velocity deviation, timetable heterogeneity, and punctuality (travel time) are compared to determine how a parameter impacts route capacity (**Section 3.3.2**).

To increase route capacity, the number of trains that can operate along the same route must be higher than capacity under the MBS. The idea is to use the VCS approach to manage a timetable. A new timetable is creased based on the VCS concept introducing the condition to determine which trains should be merged into a train convoy (**Section 3.4.2.3**), introducing the condition used to determined how many trains should be merged into a train convoy (**Section 3.4.2.4**) and proposing the equation to calculate an optimal merging velocity of an involved train (**Section 3.4.2.7)**

The approach for building a delayed train and an impacted train into the same train convoy to reduce delay is shown in the **Section 3.5**. The VCS approaches that can be used in operating state consist of four applications including the application used to create a train convoy when a train delays (**Section 3.5.1**), the application used to create a new train convoy when trains are passing a junction (**Section 3.5.2**), the approach for building a train convoy in the case that the involved trains can operate on-time (**Section 3.5.3**), and the application used to re-determine a group of involved trains when an involved train is delayed (**Section 3.5.4**)..

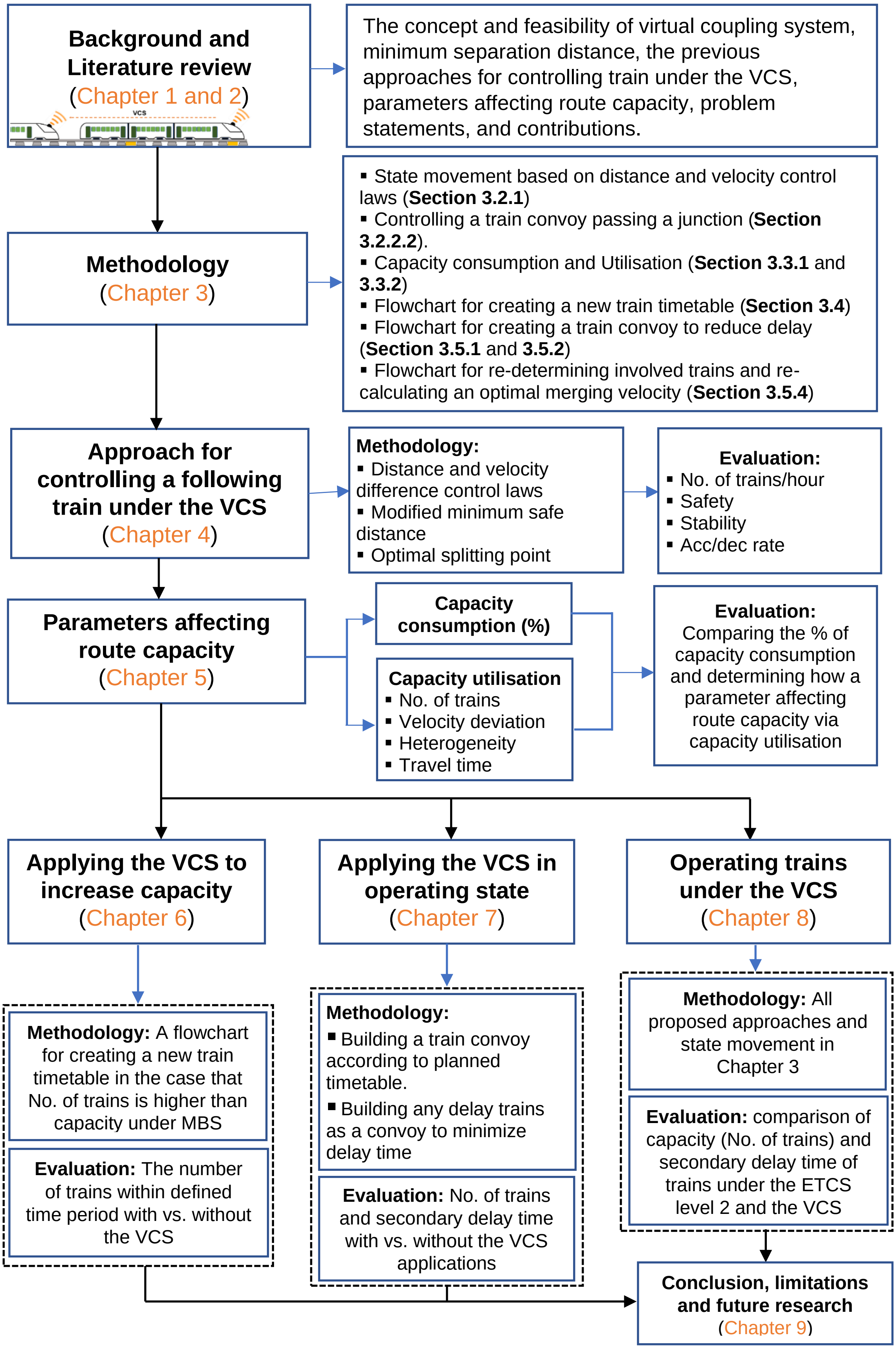


Figure 1.1 Methodology framework

1.5 Contributions

It is important to focus on the state movement applied to controlling trains operating under the VCS, the approach to managing train timetables (Creating a new timetable) for identifying when and how the VCS is applied, and the VCS applications used in the operating state to increase route capacity and reduce delay.

This thesis aims to propose the approaches based on the VCS that could be used to control trains operating under the VCS effectively, to introduce the flowchart to create a new timetable (to increase route capacity), and to introduce VCS applications used in operating state (to increase route capacity and reduce delay). By adopting this thesis, the next generation of a train signalling system - the virtual coupling system - could focus on reducing the current weaknesses including lower capacity, and unsafe and unstable movement. Such improvement comes by proposing new approaches to building a train convoy. Simulation results and analysis show that the proposed approach is effective in controlling trains operating under the VCS.

Building a train convoy by using different parameter values may result in different capacity. This thesis also aims to provide a guideline for building a train convoy. The parameters that may affect route capacity are evaluated. Simulation results and analysis will show which parameters most significantly affect route capacity.

Such methods ensure that route capacity under the VCS can be increased in that the number of trains that can operate along the same route is higher than capacity under the MBS. In this thesis, the flowchart to create a new timetable based on the number of trains is introduced. We can determine whether the VCS should be used, identify which trains and how many trains should be merged into the same convoy, and can calculate the optimal velocity that a train should proceed for merged into a train convoy. With the analysis, it is expected that the route capacity could be increased, in which the number of trains that could operate along the same route is higher than the route capacity under the MBS.

Another benefit that could be obtained from the VCS is the decrease in secondary delay. The VCS applications used in the operating are proposed. It is expected to prove that delay can be reduced, in that an impacted train will not be forced to decelerate instantly although the separation distance between them is shorter than the absolute braking distance. It will be merged into the same convoy with a delayed train in front. Building them together into the same train convoy could reduce delay of a following train. With the simulation result, it is expected to prove that the secondary delay could be avoided or reduced.

Therefore, this thesis provides the following contributions:

- Reliability equations for calculating minimum safe distance for plain route, converging, and diverging junction.
- Development of the approach used for creating a train convoy and for controlling trains operating under the VCS effectively.
- Reliability approach for controlling a train convoy passing through a junction safely.
- Guidelines for building a train convoy.
- An effective approach for creating a new timetable (managing train timetable) to increase route capacity.
- An effective approach for building a train convoy to reduce delay.

Chapter 2
Literature Review

According to the estimated railway passenger demand by D-rail (2012), the number of passengers in 2050 will be increased by approximately 40%. Such a situation will cause a big problem to railway service providers, in which they need to increase the number of train services for supporting the huge number of passengers. Constructing new routes may not be a good solution because of limitation on available space and investment funds. Thus, the effective solution is to operate more trains on the existing route. However, in some routes, trains operate in saturated condition, in which the percentage of unused capacity is not enough to insert an extra train to proceed on the same route. Adding more trains can impact badly on train operation and can increase the number of cancelled or significant delayed trains.

A new signalling system called the Moving Block Signalling (MBS) is being introduced. The track side equipment will be removed and replaced by the on-board computer used for calculating the braking curve. A train is separated from a train in front by at least the absolute braking distance which depends on the operating velocity and braking capability of a train itself. Although the performance of the MBS is better than the FBS, it still might not be sufficient to meet the predicted increase in passenger demand. Especially for high-speed trains, the separation distance between trains can be longer than 5 km. (Quaglietta, 2019a). Thus, the big challenge to operating more trains on existing routes is to reduce the separation distance between trains to increase the rate of unused capacity.

A system called the Virtual Coupling System (VCS) is proposed for increasing route capacity by allowing trains operating closer to each other. Two successive trains are separated by just the relative braking distance. The relative braking distance (the minimum safe distance) depends on operating velocity of a couple of trains and braking capability of a following train. It is much shorter than the minimum safe distance required for FBS and MBS. Following the operational concept of this system, trains will be merged into the same group as a train convoy. A following train will operate relative to the movement of the train ahead for maintaining safe distance between them. Thus, the distance between trains could be reduced with guaranteed safe separation distance through operating state (Felez, Kim, & Borrelli, 2019). With the decrease of the required distance between trains, additional trains can be added to operate along the same route increasing route capacity.

The feasibility of train operation under the VCS has been studied in many railway programs such as the European Shift2Rail programme (Goverde, 2020), and the Digital Railway Programme (NetworkRail, 2021). Their purposes are to introduce the effective signalling system, technology, and approach to control trains to increase route capacity, to reduce delay, and to improve safety of train operation.

The concept of the VCS, the feasibility of the system, and the limitations when trains operate under the system are explained in **Section 2.1**. Then, the minimum safe distance required when trains operate along plain route, and when approach a junction is shown in **Section 2.2**. Previously suggested approaches that could be used to control trains operating under the VCS are summarized in **Section 2.3.** It is noted that these approaches are used to control trains proceeding along plain route. In **Section 2.4**, the approach used to control a group of trains (a train convoy) when approaching a junction is shown. After that, in **Section 2.5**, the situation when the VCS will be (or should be) applied to control trains as a train convoy is determined. According to the previous studies, the distance between trains could be different depending various parameters such as velocity, braking rate, etc. Thus, in the last section (**Section 2.6**), the parameters that may impact on the length of safe distance are reviewed.

2.1 Train Virtual Coupling System

Trains could not proceed across the area that has different ATP systems limiting the transportation across countries because of the different national requirements and standards. To solve this limitation, the European Rail Traffic Management System (ERTMS) has been introduced as the international signalling control to develop the railway operation performance (Shift2Rail, 2015; RSSB, 2017). Currently, the signalling system based on ERTMS consist of four levels (See more detail in **Appendix B**). In the thesis, we focus on the ETCS level 4 which has been developed for increasing route capacity and reducing delay.

2.1.1 The concept of virtual coupling system

Figure 2.1 shows the system architecture of the MBS compared to the VCS. For the MBS, a train position is continuously sent to the RBC via the communication system between vehicle and infrastructure (V2I). The RBC receives train data (ID, position) and then calculates the Movement authority (MA) indicating the point of End of Authority (EoA) and Supervised Location

(SvL) which is sent back to trains within the control area. The successive trains under the MBS are separated by the absolute braking distance ($\mathrm{MA}_{\mathrm{MBS}}$) plus safety margin (SM) caused from the system and communication delay.

The system architecture of the VCS in terms of functionality and technology are assumed to be similar to the MBS (Quaglietta & Goverde, 2019a). However, a train will send the data (via vehicle to vehicle, V2V communication system) to its following train instead. The train data: velocity, position, and route are sent to a train proceeding behind to determine movement authority (optimal velocity and acceleration/deceleration rate). It is noted that the first train in a train convoy still operates under the MBS (**Figure 2.2**). The main difference between MBS and VCS is the minimum safe distance between successive trains. The minimum safe distance under the VCS is shorter than the distance required for the MBS based on the fact that a train does not stop dead after applying brakes. Thus, successive trains under the VCS are separated by relative braking distance which will be minimized when they are in the convoy state (Flammini et al., 2018).

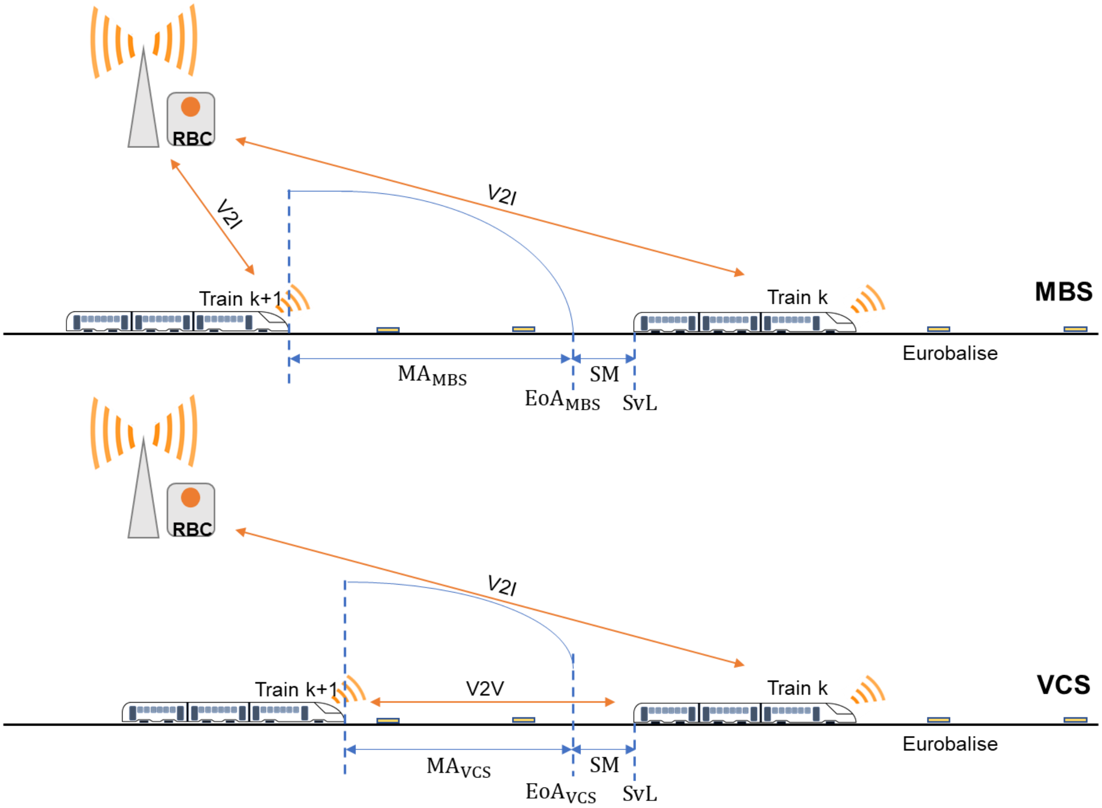


Figure 2.1 System architecture of the MBS and the VCS

2.1.2 Operating under the virtual coupling system

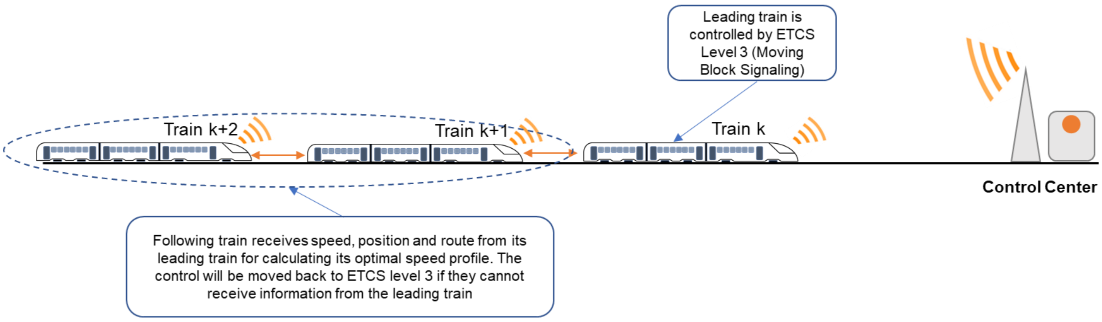
Before building trains into a train convoy, a following train will send the convoy proposal requesting to be merged with a train in front. The convoy proposal will be accepted depending on the conditions for merged as a train convoy. There are a few studies introduced the conditions for determining the convoy proposal. Aoun, Quaglietta, & Goverde (2020) sugested that convoy proposal should be sent for requesting to join with a front train when the distance seperated from a front train is shorter than minimum safe distance under the main signalling control. The convoy proposal must be accepted before allowing a train to join.

After accepting the convoy proposal, there are three states to switch from MBS to VCS (Zhang & Zhang, 2020). At the first state, a following train receives the information including position, velocity, and route information from a leading train via V2V communication system. Then, a train will cancel wayside equipment such as track circuit. In this state, train information and train integrity have been automatically checked and have reported to the train running behind for calculating MA for a following train. After that, a following train will be equipped with the MA module in that it can calculate optimal velocity and braking rate and can proceed according to the movement of its leading train. When a group of trains operates under the VCS, the minimum safe distance between successive trains depends on the route characteristic. It will be increased when trains need to pass a junction or approach a station. Due to different minimum safe distances, six operational scenarios should be considered (Mendes & Quaglietta, 2021).

- Operating along plain route
- Operating along plain route and then approaching a station
- Passing through a converging junction
- Passing through a converging junction and then approaching a station
- Passing through a diverging junction
- Passing through a diverging junction and then approaching a station

As the operation under the VCS relies on the communication between trains, it might create a higher risk due to the complexity of communication layer (Aoun, Quaglietta, & Goverde, 2020).

Once trains operate under the VCS, there are 3 moving states including merging, convoying, and splitting states. At the merging state, a following train proceeds using a higher velocity than a train in front for shortening the distance between them. A following train will be forced to decelerate to the same velocity as a leading train when the separation distance between them is in the acceptable safe distance. When the distance between successive trains is in acceptable range of safe distance and operating velocity of both trains is equal, they are in the convoying state. A following train will proceed relating to a leading train's movement. It will accelerate if a leading train accelerates, decelerate when a leading train slow down, and proceed by the same velocity as a leading train if a leading train operates by constant velocity. The movement authority (MA) of a following train can be calculated by the train itself using the information received from a leading train. When a train convoy approaches a junction and successive trains in a convoy continue on different routes, the distance between them must be lengthened to at least the minimum safe distance at a junction. This state is called splitting state, in which a following train may be forced to operate by a lower velocity than its front train for lengthening the distance between them.



Leading train is controlled by ETCS Level 3 (Moving Block Signaling)

Following train receives speed, position and route from its leading train for calculating its optimal speed profile. The control will be moved back to ETCS level 3 if they cannot receive information from the leading train

Figure 2.2 Train virtual coupling system (Modified from Mitchell (2016))

When the separation distance between trains is longer than minimum safe distance required for passing a junction, the communication between them will break up allowing each train operate independently (Konig & Schnieder, 2001). In the case that communication between trains is lost, the train operation must be switched back to non-convoy state where trains will be back to operate under the MBS.

2.1.3 Feasibility of train virtual coupling system

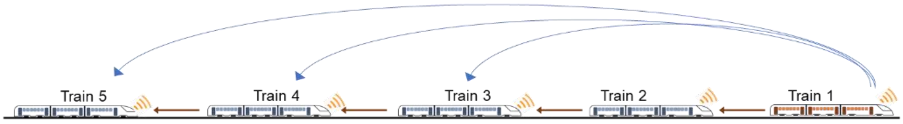
To control trains operating under the VCS, three main parts must be developed for helping trains moving closer to each other. First is to develop autonomous train operation. It is suggested that all on board equipment should achieve safety integrity level (SIL) 2 and meets the CENELEC standard (EN50126/8/9) except the driver machine interface which requires at least SIL 2 (Ramdas et al., 2010). The autonomous operation system used in the MBS operation has recently been developed. However, it cannot be used in the VCS yet but the whole system is possible to control trains running based on the VCS. The communication system must be developed allowing trains to send and receive the information between them.

Second, the accuracy and reliability of the detection system should be improved. The detection system such as balise and odometer is currently used in the ERTMS to detect position and velocity of a train. According to the study by Malvezzi et al. (2011) and Jiang et al. (2018), the odometer can be used to measure the position of the trains with high accuracy. Thus, the train operation under the VCS is possible and reliable. It could ensure that trains could operate safely, in which the distance between trains is longer than minimum safe distance. The accuracy of the velocity and position of a train is very important because a following train needs the accurate information of a leading train to identify the next braking point and to create the optimal velocity profile. The results from the previous studies show that the detected velocity obtained from the odometer is significantly close to the actual velocity. The study by Malvezzi et al. (2011) shows that the odometer can be used for detecting train velocity accurately with only approximately 0.9 – 2.9 percent error.

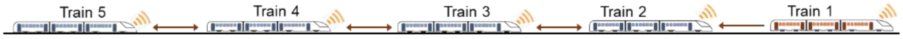
Third, the communication time between trains should be reduced. A higher communication time will decrease route capacity, in which a train will need more time to adjust its velocity according to a leading train movement. Thus, the route capacity can be increased by reducing the communication time between trains, and/or between train and control centre. Currently, the communication system via wireless control is possible, available, and reliable. The system should achieve at least SIL 2 (Garcia, Lehner, Strang, & Frank, 2008).

Figure 2.3 shows six types of communication typology between trains. Referring to previous approaches used to control trains operating under the VCS such as the approaches by KePing Li and ZiToy Gao (2011), Henke and Trachtler (2013), and Quaglietta and Goverde (2019a), the MA of a following train is calculated by using a leading train data. Thus, the predecessor following typology (**Figure 2.3 (A)**) can be used. Meo, Vaio, Flammini, and Nardone (2020) suggested that the predecessor-following leader typology (**Figure 2.3 (C)**) should be used for communicating trains operating under the VCS. Based on this communication type, a following train can both send and receive the data from a leading train. It will be used in the case that successive trains have different maximum velocity. In the case that a following train (slower train) proceed its maximum velocity catching up with a leading train (higher velocity), a following train can send its information requiring a leading train to slow down allowing a following train to be merged.

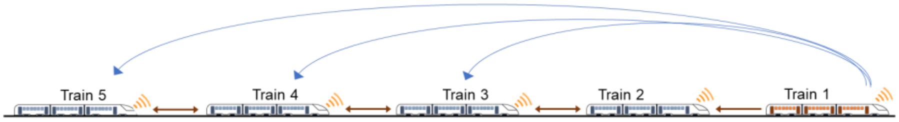
(A) Predecessor following typology



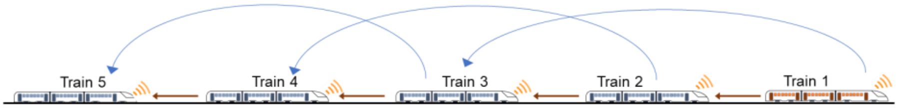
(B) Bidirectional typology



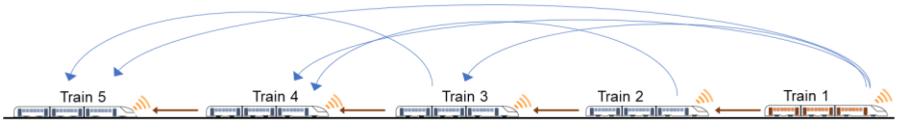
(C) Predecessor-following leader typology



(D) Bidirectional leader typology



(E) Two predecessor-following typology



(F) Two predecessor-following leader typology

Figure 2.3 Types of communication topology (S. E. Li et al., 2017)

Similar to the suggestion by Quaglietta (2019b), data on a following train such as maximum braking rate, maximum velocity, etc. should be sent from a following train to a leading train for safety reasons. This is because the collision between trains might occur if a following train could brake by a lower rate than a leading train. It would be better if a leading train knows the braking capability of its following train. Tt could adjust its braking rate relating to the braking rate of a train behind. Thus, it could be concluded that the control strategies should be designed based on the communication topology (Saxena, Li, Goswami, & Math, 2016).

2.1.4 Strengths, weakness, and safety issue

It is well known that the main benefit obtained from the VCS is the increase in route capacity and the reduction in delay. However, there are many shortcomings, especially the potential safety issues. The strengths and weaknesses of the VCS are summarized in the **Table 2.1**.

Table 2.1 Strengths and weaknesses of the VCS (Modified from Aoun et al. (2020))

Strengths	Weaknesses
▪ Increasing route capacity as a shorter separation distance between successive trains. ▪ Reducing delay. ▪ Eliminating communication time between trains and the control center. ▪ Reducing cost of trackside equipment. ▪ Providing flexibility service. ▪ Reducing accident (the system relies on communication between trains). ▪ Reducing energy consumption (a train convoy proceeds as a single train reducing stop and go movement).	▪ Based on current switch equipment technology, a train still needs absolute braking distance separated from the train ahead when passing a junction. ▪ The accident might occur if a following train brakes using a lower rate than a front train. ▪ Increasing cost of communication system. ▪ It is important to upgrade all infrastructure.

The train operation under the VCS also provides many benefits to the customers. A train will arrive in time because it could recover its timetable by merging itself with a front train to reduce delay (Bock & Bikker, 2000). Thus, it could be said that building trains as a train convoy not only increases route capacity but also reduces delay. It is proved by the study by Rivera, Dick, and Evans (2020) who studied the benefit from building trains as a train convoy. They found that merging a group of trains as a train convoy could decrease delay. However, it must be ensured that the train information including position, velocity, and route information is measured correctly.

The information recorded in different trains may not be the same due to the different operation plans (Zhang & Wang, 2020). Incorrected information may increase the possibility of collision between trains. High risk of collision generally occurs in the case the maximum braking rate of a leading train is higher than the braking capability of a following train (M. Chen, Xun, & Liu, 2020). Thus, to operate a group of trains under the VCS safely, it is important to ensure that the trains which are built into the same convoy have the same braking performance.

2.2 Minimum safe distance under the VCS

Table 2.2 shows the equations to calculate minimum safe distance under MBS and VCS. The minimum safe distance between successive trains directly depends on velocity limit ($\mathrm{v^{max}}$) or operating velocity ($\mathrm{v_{k+1}(t)}$), safety margin (SM), and maximum braking rate of the train itself ($\mathrm{b^{max}_{k+1}}$). Thus, successive trains are separated by absolute braking distance (Ates & Ustoglu, 2018). It is different from the required safe distance between trains under the VCS. The minimum safe distance under the VCS relies on the relative operating velocity of a couple of trains (a leading and a following train) and maximum braking rate of a following train..

Table 2.2 Minimum safe distance under MBS and VCS (Modified from Y. Zhao, Orlik, and Kalmar-Nagy (2015))

Control	Min. safe distance	Comment
MBS	$\Delta \mathrm{x_k^{MBS}} = \frac{(\mathrm{v^{max}})^2}{2\mathrm{b^{max}_{k+1}}} + \mathrm{SM}$	The worst-case braking distance depends on the velocity limit restricted along the route ($\mathrm{v^{max}}$) and the maximum braking rate ($\mathrm{b^{max}_{k+1}}$) of a train itself.
	$\Delta \mathrm{x_k^{MBS}(t)} = \frac{\mathrm{v^{max}v_{k+1}(t)}}{2\mathrm{b^{max}_{k+1}}} + \mathrm{SM}$	It is calculated by using the velocity limit ($\mathrm{v^{max}}$), current train's velocity ($\mathrm{v_{k+1}(t)}$), and maximum braking rate of a following train ($\mathrm{b^{max}_{k+1}}$).
	$\Delta \mathrm{x_k^{MBS}(t)} = \frac{\mathrm{v^2_{k+1}(t)}}{2\mathrm{b^{max}_{k+1}}} + \mathrm{SM}$	The safe distance depends on current velocity that a following train has operated and maximum braking rate of a following train itself.
VCS	$\Delta \mathrm{x_k^{VCS}(t)} = \frac{\mathrm{v^2_{k+1}(t) - v^2_k(t)}}{2\mathrm{b^{max}_{k+1}}} + \mathrm{SM}$	The minimum separation distance between trains is reduced compared to other system. It relies on the difference of current velocity between two adjacent trains and the braking rate of a following train.

One important factor used for calculating the minimum safe distance in both signaling controls is the Safety Margin (SM). The SM is added into the safe distance equation in order to reduce the risk of collision caused from the communication delay, detection system delay, driver response time, etc.

Table 2.3 shows the example of the SM distance added into the equation to calculate the minimum safe distance between trains under the ETCS Level 2. The minimum safe distance between trains under the ETCS level 2 relies on the absolute braking distance plus safety margin (SM) including the train protection system, ETCS, driver response and driver assisting time, train location detection system, interlocking, and communication time between train and control centre. It is slightly different from the ETCS level 3 (MBS) in that the time compensated for detecting and reporting the interlocking process is not included because the track side equipment and the detection system along the line are removed (Europa, 2020; Stacy, 2017). The lineside signalling is not required for controlling train‘s spacing because the length of block is not fixed and could be varied relaying on the train's velocity (Ngai, 2010). Thus, the interlocking operation time and delay due to section length are eliminated from the SM under the MBS. Under the MBS, a train's position has directly been sent to the control centre instead of the track side detection equipment (UNIFE, 2018).

Table 2.3 Safety margin (SM) required for ETCS level 2 (McNaughton, 2011)

Element	Headway (sec)	Commend
1) Train capability	1	ETCS response time.
	3	Brake operation time.
2) Driver response	6	Time that a train driver response to the displayed data to operate the control.
3) Train position system	5	Position detection tolerance.
4) Train location section	16	Time error due to the distance between detection devices (section length).
5) Driver response assist	3	System operation time (Time to input data to display at the user interface).
6) Interlocking	2	Interlocking process (detect and report)
7) Turnout operation time	12	Detection and operation time of the junction equipment.
8) Movement authority	7	The time that the MA sent from the RBC to the train.

Train position is detected by the detection equipment called “Euro-balise” which normally are installed every 500 m along the route (Ramdas et al., 2010). The transmission of balise will take approximately 5 sec for 100 m/s operating velocity. It is recommended that the data should continuously be reported to the RBC in every 5 sec. Therefore, the communication time between trains and RBC, and the time to detect a train position must be added to the minimum separation time under the MBS. The **Figure 2.4** shows the elements of minimum safe distance between trains under the MBS. The distance between a couple of trains is separated by the absolute braking distance and safety margin due to train system delay, driver response time, train’s position delay, data input process, data transmission, detection equipment spacing, and the MA time.

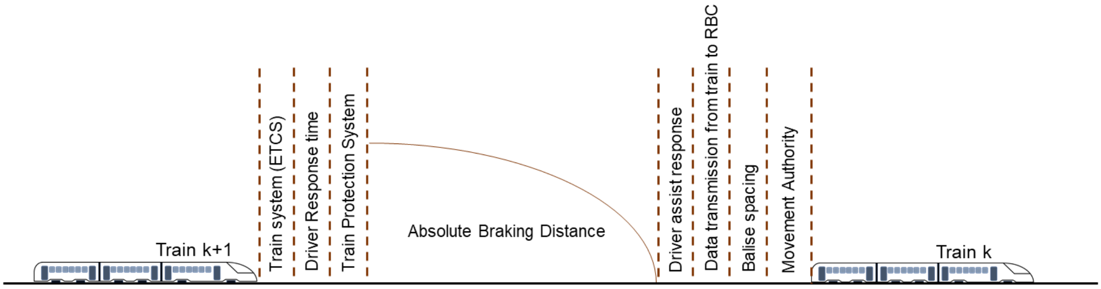


Figure 2.4 Minimum safe distance under the MBS (McNaughton (2011a))

Similar to operation of trains under the VCS, the SM elements for MBS could be used as the safety margin required for the VCS. Thus, successive trains under the VCS are separated by the relative braking distance plus the SM due to the system operation time as shown in **Figure 2.4**. The minimum safe distance decreases with the decrease in velocity difference between two successive trains. The minimum safe distance will be minimized when a couple of trains are operating with the same velocity, in which successive trains will be separated by only safety margin. The minimum safe distance under the VCS is not a fixed value but could be changed depending on operational parameters (velocity and braking rate). In addition, it could be different depending on route detail (plain route, junction, station).

2.2.1 Minimum safe distance for plain route

The separation distance between trains refers to the distance from the head of a following train to the rear of a front train. It is increased if a following train operates by a lower velocity than its front train and decreased if a following train moves by a higher velocity. The minimum safe distance between trains under the MBS can be calculated by using the **Equation (2-1)**. It relies on the current velocity ($v_{k+1}(t)$) and maximum braking rate (b_{k+1}^{max}) of a following train (Ning, 1998). The minimum safe distance between successive trains is the instantaneous braking distance required by a following train plus a safety margin (Y. Wang, Schutter, Boom, & Ning, 2013).

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

When the signalling system is switched from the MBS to the VCS, we can assume that the probability that a leading train stops dead is extremely small and nearly close to zero. In the other words, a leading train does not suddenly stop at the point that it begins applying brake, but it can continue proceeding forwards at deceleration rate.

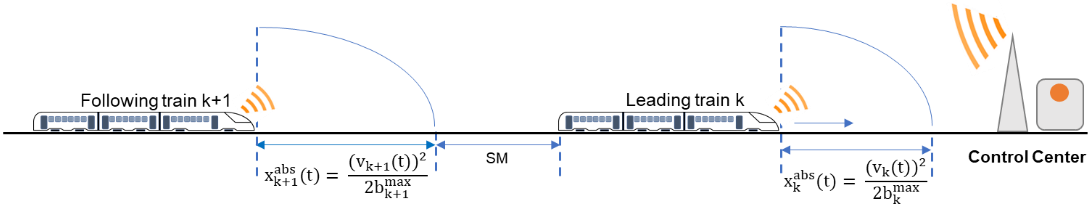


Figure 2.5 Trains’ movement under the MBS

The movement behaviour of a couple of trains under the MBS is shown in **Figure 2.5**. The difference of travelling distance between two trains after braking is

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

It is assumed that the maximum braking rate of all trains built into the same convoy is equal ($b_k^{max} = b_{k+1}^{max} =, \dots, b_N^{max}$). Then, the minimum safe distance between trains at the time t can be calculated by **Equation (2-3)**.

$$\Delta x_k^{min}(t) = \left(\frac{(v_{k+1}(t))^2 - (v_k(t))^2}{2b_{k+1}^{max}} + SM\right) \tag{2-3}$$

According to the minimum safe distance equation in **Equation (2-3)**, the distance between successive trains could be shorter than the safety margin in the case that a following train proceeds by a lower velocity. However, to ensure safety, Q. Wang, Chai, Liu, and Tang (2021) suggested that successive trains under the VCS should be separated by at least safety margin (SM). This is because when trains under the VCS are in the convoy state where the velocity of the successive trains is equal, there is no impact of different operating velocities. So, both trains will cover the same distance for braking.

2.2.2 Minimum safe distance at a converging junction

When a train convoy is approaching a converging junction, it could proceed passing a junction safely based on the conditions as it proceed along the route. A following train is not forced to proceed by a lower velocity for extending distance from a leading train. As a result, the capacity at a junction could be increased compared to the capacity under the MBS. Thanks to the ETCS performance in which it knows the route set and junction’s speed limit. The braking curve can be created according to these data (Mirse, 2018). Trains from different routes could be inserted into the same route at a converging junction. A difficult situation is how a train from another route could be inserted into the main route safely. The switch equipment must be completely set before allowing the next train to pass. The distance between a train on the main route and an inserted train must not be shorter than the absolute braking distance plus safety margin and the distance due to junction operation time (**Figure 2.6**). Following the recommendation by Goverde (2020), a train on the main route has to slow down to junction velocity limit when it approaches a junction. After passing a junction, the turnout will be switched for the next train.

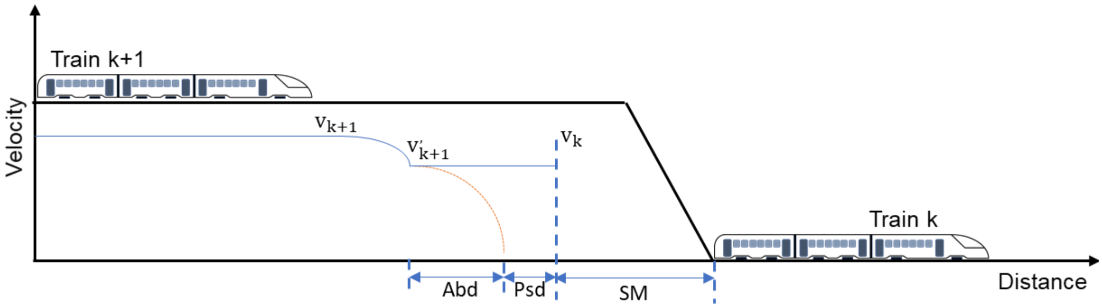


Figure 2.6 Minimum safe distance between trains under the VCS at a converging junction (Modified from Quaglietta (2019a))

In some route, the trains on the main route could pass a junction by using a higher velocity than an inserted train. The minimum safe distance between trains may be increased due to different velocities when passing a junction.

2.2.2.1 Inserted behind a faster train

The minimum safe distance between trains from different routes when approaching a converging junction is shown in the **Figure 2.7**. Assuming that an inserted train (m) and a train on the main route pass a junction by different velocity. A slower train (m) will be inserted into the same route as a faster train (k). The faster train needs to pass a junction by its whole length before allowing the turnout moves back and then set for a slower train (m).

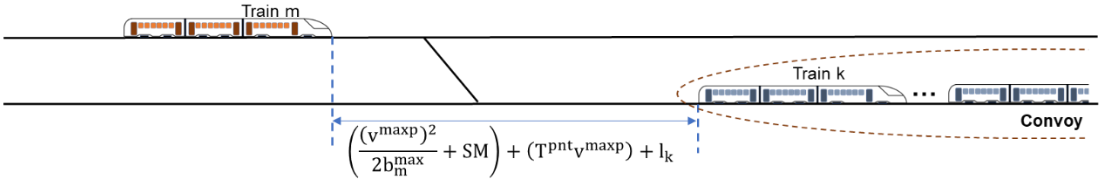


Figure 2.7 Inserted behind a faster train

The distance due to the junction operation time (T^{pnt}) and the length of the last train in a train convoy (l_k) are added into **Equation (2-3)** to calculate minimum safe distance at a converging junction. Thus, the minimum safe distance from a slower train (m) and a faster train (k) when passing a converging junction (Δx_k^{cvr}) can be calculated by **Equation (2-4)**, where v^{maxp} is a junction velocity limit or the highest velocity that a slower train (m) could pass a junction.

$$\Delta x_{k,m}^{mcvr} = \left(\frac{(v^{maxp})^2}{2b_m^{max}} + SM\right) + (T^{pnt}v^{maxp}) + l_k \qquad (2\text{-}4)$$

2.2.2.2 Inserted in front of a faster train

In the case that a slower train (m) is inserted into the route in front of a faster train (**Figure 2.8**), using the minimum safe distance as shown in **Equation (2-4)** might not be safe. The distance between trains has been reduced due to a lower velocity of a front train. Thus, the distance due to different velocities (Δx_m^{cps}) must be added into the minimum safe distance equation to ensure that trains could pass a junction safely. Following the recommendation by McNaughton (2011a), the compensated distance (Δx_m^{cps}) could be estimated by **Equation (2-5)**.

$$\Delta x_m^{cps} = \Delta x_k^{tacc} - \Delta x_m^{tacc} = 0.5b_m(\Delta t_m^{acc})^2 \qquad (2\text{-}5)$$

Assuming that a slower train (m) approach a junction by v^{maxp} and will be inserted into the route by v^{maxp}. It will accelerate to the maximum velocity (v^{max}) after passing a junction. The time that the train accelerates from v^{maxp} to v^{max} is $\Delta t_m^{acc} = (v^{max} - v^{maxp})/a_m$. For the same time period, the distance covered by a faster train (a following train, k) is $\Delta x_k^{tacc} = v^{max}\Delta t_m^{acc}$ while the distance covered by the inserted train is $\Delta x_m^{tacc} = v^{maxp}\Delta t_m^{acc} - 0.5b_m(\Delta t_m^{acc})^2$.

Example 2-1: it is assumed that the velocity limit restricted along the route and at the junction is 60 m/s and 30 m/s respectively. A slower train is inserted into the main route and then pass the junction by 30 m/s. Then, it accelerates by 0.5 m/s^2 to 60 m/s after passing the junction. 60 sec or 2.7 km is spent for accelerating from 30 m/s to 60 m/s. For the same time period, the distance covered by the train on the main route (the train will pass the junction by 60 m/s) is 3.6 km. Thus, the required minimum separation distance between train should be widen by 0.9 km.

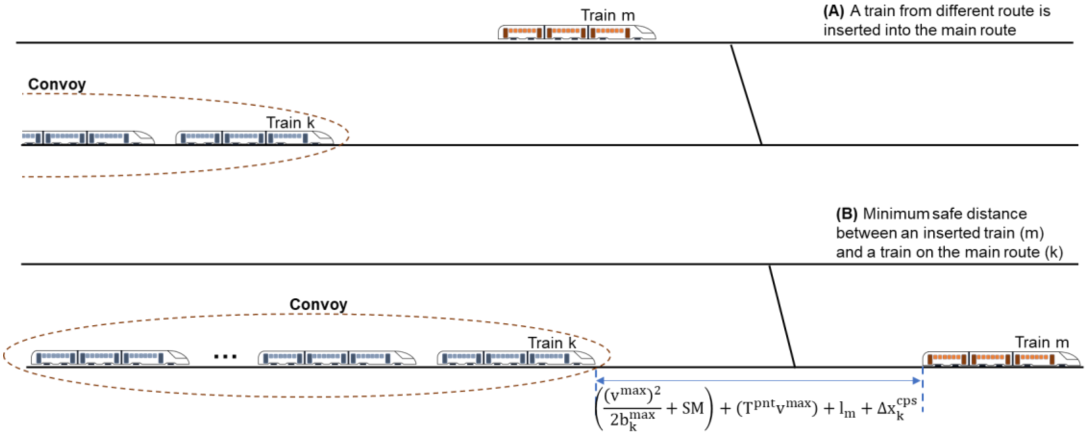


Figure 2.8 Inserted in front of a faster train

Therefore, the minimum safe between trains at a converging junction in the case that a train in front pass a junction by a lower velocity can be calculated by the **Equation (2-6)**.

$$\Delta x_{m,k}^{mcvr} = \left(\frac{(v^{max})^2}{2b_k^{max}} + SM\right) + (T^{pnt}v^{max}) + l_m + \Delta x_m^{cps} \qquad (2\text{-}6)$$

2.2.3 Minimum safe distance at a diverging junction

It is ensured that a train convoy can proceed safely when successive trains in a convoy are separated by relative braking distance. However, it is safe for only the case that the trains proceed along the plain route (no junction). When a train convoy pass a diverging junction where any successive trains may continue on different route, the distance between trains must not be shorter than minimum safe distance at a junction. The minimum safe distance at a diverging junction is normally longer than minimum safe distance for plain route due to a switch point operation time. Consequently, a following train will be forced to operate by a lower velocity for extending distance separated from a train ahead. As such a distance extension, the capacity obtained from the VCS will be the same compared to the capacity gained from the MBS (Quaglietta, 2019b).

McNaughton (2011a) reviews the minimum safe distance for high-speed trains when proceeding along plain route and passing junction. He suggested that the additional distance due to the deceleration and switch point operation time must be added into the minimum safe distance for plain route to ensure safety. Similar to the suggestion by Connor (2013), he explained that the next train will be allowed to pass a junction when a switch point equipment is completely locked for the approaching train. So, the additional term due to the switch point operation time (T^{pnt}), which could be roughly estimated by $T^{pnt}v^{max}$, must be added to the equations for calculating minimum safe distance for the plain route. **Figure 2.9** shows the minimum safe distance between trains when passing a diverging junction. The distance between trains must be longer than the absolute braking distance plus SM and distance due to switch point operation time (**Equation (2-7)**).

$$\Delta x_k^{dvr} = \left(\frac{(v^{max})^2}{2b_{k+1}^{max}} + SM\right) + (T^{pnt}v^{max}) + l_k \tag{2-7}$$

However, the challenge is to identify the optimal point that a following train should start splitting from a train convoy to obtain safe distance separated from the front train. Another challenge is to control train stopping safely if switch point equipment could not completely be set at for the nest train on-time. Haixiao Duan, Yang, Duan, and Zhang (2020) suggested that a following train should be at, at least, the safe point when the switch is completed locked for the next train. The safe point is located in front of a junction for ensuring that a train can stop before reaching the junction.

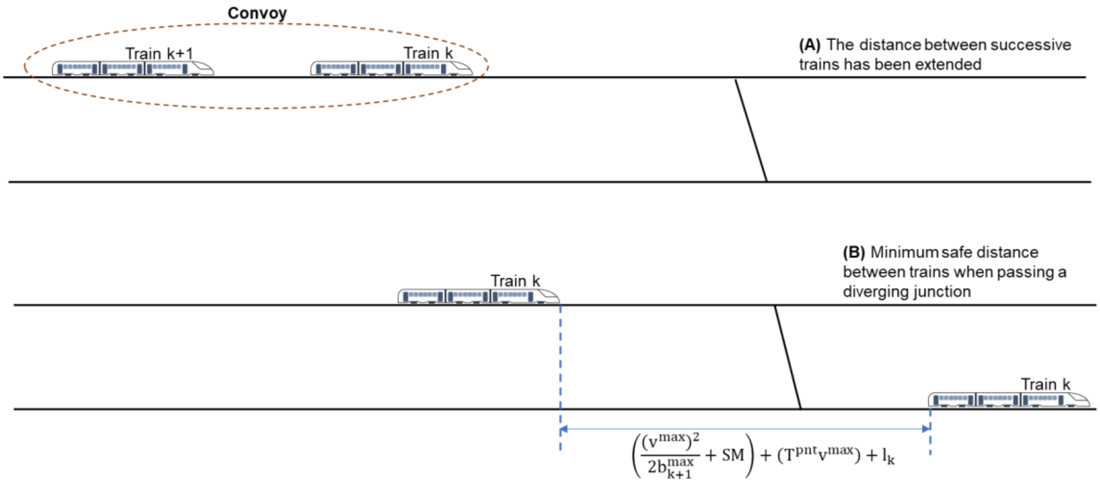


Figure 2.9 Minimum safe distance at a diverging junction (Modified from Quaglietta (2019a))

2.3 Controlling trains operating under the VCS

There are many approaches introduced for controlling trains operating under the VCS. They were created based on different theories such as discrete event model (Xu, Li, & Yang, 2014), discrete-time model (Yang, Li, Gao, & Li, 2010), cellular automation model (K.-P. Li & Fan, 2010; Zhou & Mi, 2013), car-following model (K. Li & Gao, 2007; K. Li & Guan, 2009; J. Ye, Li, & Jin, 2013), distance difference control laws (K. Li, Gao, & Ning, 2005), and the distance and velocity difference model (Henke, Ticht, Schneider, Bocker, & Schafer, 2008; Henke & Trachtler, 2013). In this thesis, the approaches created based on the concept of car-following model, distance difference control laws, and distance and velocity difference control laws are reviewed.

2.3.1 Approaches based on car-following model

Most of previous approaches were developed using the concept of the car-following model. This is because the movement of a following train when operating under the VCS is similar to the car proceeding on a road highway. The traditional optimal velocity car-following model was proposed by Bando, Hasebe, Nakayama, Shibata, and Sugiyama (1995). Based on the model, a following vehicle will adjust the distance closed to safe distance separated from a front vehicle. Due to wide range of deceleration and acceleration rate of a vehicle movement in road traffic, the car-following model might not be well to control trains under the VCS. Collision between trains may occur if a train braked by using a lower braking rate than calculated braking rate.

K. Li and Guan (2009) introduced an additional term into the traditional optimal velocity car-following model for limiting the range of deceleration and acceleration rate. The simulated results show that their proposed model is effective to simulate a following train movement, in that the rate of acceleration/deceleration are mostly limited in realistic range. Similar to the study by K.-P. Li, Gao, and Tang (2011), the range 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 a train velocity profile. KePing Li and ZiToy Gao (2011) also improved the optimal velocity car-following model to shorten the separation distance between trains under the FBS. Based on their model, the train could proceed forward although the signal is red reducing the separation distance between successive trains proceeding on the same route. The ideal velocity profile to bring a train arriving on time could be created by using the car-following model. J.-J. Ye and Li (2013) created an approach based on optimal velocity car-following model to control trains as a train convoy. The purpose is to recover train timetable to bring a train to the destination on time. Their simulation result shows that a group of trains could operate as a single train and could arrive at the destination on time.

However, one obvious problem from the previous approaches based on the car following model is unstable travelling. A train could not maintain stable travelling due to the fluctuation of optimal velocity calculated by these approaches.

2.3.2 Approaches based on distance difference control laws

Using the approaches based on the car-following model may be unsafe because the distance between trains could be shorter than minimum safe distance. In addition, a train speed may not be stable. To solve these shortcomings, the approach based on distance difference control law has been introduced. The main idea is to adjust the distance between trains and the minimum safe distance as close as possible. K. Li, Gao, and Ning (2005) proposed a new railway traffic model to control trains operating as a train convoy under the MBS. Based on their model, the movement of a following train directly depends on the distance separated from its leading train. It will accelerate if the distance from a front train is longer than the minimum safe distance and will decelerate when the distance is shorter than minimum safe distance. Similar to the train following model proposed by K. Li and Gao (2007), the same condition is used to simulate train movement under the MBS. It is found that the proposed approach could be used well for simulating a following train movement under the MBS. R. Liu and Golovitcher (2003) introduced the additional term related to the difference between the actual and minimum safe distance to determine the interaction between two successive trains. The simulated result is similar to other previous approaches that could be guaranteed that trains could proceed safely.

Moreover, using the concept of the distance difference control law to control trains as a train convoy could reduce the rate of energy consumption. C.-X. Cao, Xu, and Li (2013) also propose the approach based on the distance control for simulating trains operating as a train convoy. Their result shows that the trains could operate as a train convoy. In addition, the rate of energy consumption is reduced because trains could proceed more stable reducing stop and go movement.

2.3.3 Approaches based on distance and velocity difference control laws

Although it is ensured that trains could operate safely as the distance between trains is controlled, trains may not obtain stable travelling. Velocity od successive trains may be different when the distance between them is equal to minimum safe distance. As a result, the distance between trains will be lengthened or shortened forcing a following to accelerate or decelerate again. The control trains proceed safely and obtain stable traveling, the distance and velocity difference control laws is applied to control trains operating as a train convoy (Henke, Vocking, Bocker, Frohleke, & Trachtler, 2005).

Pan and Zheng (2014) introduced three control laws based on the velocity and distance difference concept to simulate train's operation under the MBS. The simulated results revealed that the acceleration rate depends on both velocity and distance difference. But when the distance between trains is shorter than minimum safe distance, a following will be forced to slow down by deceleration rate that relies on its operating velocity only. As a result, the distance between trains might still be shorter than the safe distance.

Henke, Ticht, et al. (2008) also proposed the approach based on distance and velocity difference control laws to simulate following train's movement under the VCS. But the velocity difference is fixed and consists of two states: merging and transferring states. At the merging state, they suggest that the velocity difference between successive trains should be 2 m/s when the separation distance is longer than the absolute braking distance. The velocity difference will be reduced from 2 m/s to 0.7 m/s when the distance between them is closer to the minimum safe distance. The simulation results show that trains operate safely in which the distance between successive trains is surely longer than the relative braking distance. In addition, trains could operate as a train convoy (convoy state), in which the velocity of both trains is equal maintaining the distance between them. Henke and Trachtler (2013) use the same velocity difference control law to control train movement but they improve the distance difference by modifying the equation to calculate minimum safe distance. They found that the distance between trains is decreased compared to the simulated distance based on the approach introduced by Henke, Ticht, et al. (2008). The route capacity is increased but the distance between trains after transferring to convoy state might be shorter than minimum safe distance.

Figure 2.10 shows the state movement based on the laws of distance and velocity difference introduced by Henke and Trachtler (2013). The operation state of trains under the VCS practically consists three states including merging, convoying (or platooning), and splitting state. A following train will be merged into a train convoy when it proceeds by a higher velocity than a front train. At the beginning, when the distance between trains is greater than the absolute braking distance, a following train will operate by maximum velocity ($\mathrm{v}^{\mathrm{max}}$) for catching up with a leading train. In this state, the velocity difference between trains is fixed at 2 m/s. When the separation distance between trains is shorter than the absolute braking distance but still longer than the relative braking distance, the velocity difference between successive trains is reduced to 0.7 m/s. A following train will decelerate to reach the target velocity difference compared to a leading train's velocity. A following train will be forced to decelerate again to proceed by the same velocity as a leading train when the separation distance between them becomes closer to the relative braking distance ($\Delta\mathrm{x}_{\mathrm{k}}^{\mathrm{rel}}$) plus an extra gap $\mathrm{x}_{\mathrm{min}}$. The extra gap $\mathrm{x}_{\mathrm{min}}$ is the distance provided in transferring state. It is the distance that a following train has covered to reduce its velocity (in the merging state) to the same velocity as its leading train. Then, both trains could operate as a single train, in which a following train will adjust its velocity according to the movement of a leading train. When a train convoy is approaching the next station, a following train uses the same control law for splitting out from a train convoy. It will decelerate to reach 0.2 m/s velocity difference for lengthening the distance from a leading train. Then, it will decelerate again for extending the velocity difference to 0.7 m/s when the distance from the front train is longer than the relative braking distance.

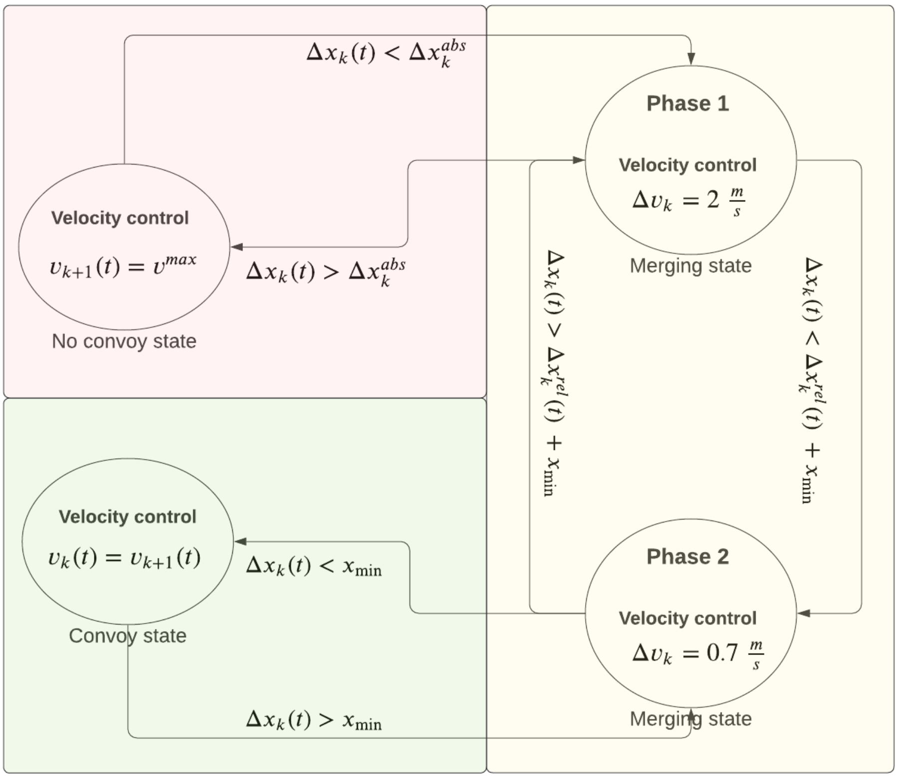


Figure 2.10 State movement for simulating trains under the VCS (Modified from Henke and Trachtler (2013))

Quaglietta and Goverde (2019) introduced the optimal point to decelerate to transfer into convoy state. The idea is to force a following train to decelerate earlier. They recommend that a couple of trains should be transferred into convoy state when the different distance between the separation distance and minimum safe distance is smaller than distance tolerance and velocity difference between trains must be lower than velocity different limit. They also suggested that the approach for controlling trains should be divided into multiple states including merging, transferring, convoying, and splitting state. The state relies on route characteristic (plain route, junction, station).

The operational states of trains under the VCS were proposed by Quaglietta (2019). Their state movement consists of four states depending on the velocity difference between successive trains (**Figure 2.11**). A following train will be merged into the same convoy with a leading train when it proceeds by a higher velocity for decreasing separation distance between trains (**Figure 2.11 (a)**).

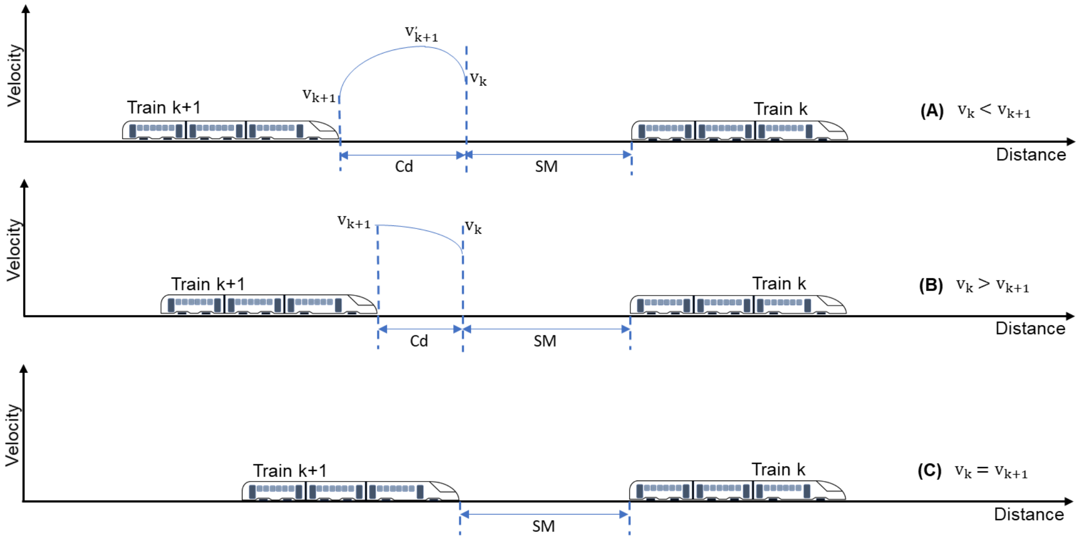


Figure 2.11 Operational state movement of trains under the VCS (modified from Quaglietta (2019))

If a following train proceeds at a lower velocity $v_k(t) > v_{k+1}(t)$, there are two possible modes including the cruising and the following mode. When a following train operates under the cruising mode, it could run at its desired velocity without catching up with its front train. If it runs by the following mode (**Figure 2.11 (b)**), it will accelerate to a higher velocity than a train ahead to be merged with a leading train. Then, it will decelerate to the same velocity as its leading train to be coupled together into a train convoy. In such a situation, a couple of trains will operate as a train convoy and velocity of both trains is equal ($v_k(t) = v_{k+1}(t)$) (**Figure 2.11 (c)**).

Haixiao Duan et al. (2020) also use the same concept to merge a group of trains into a train convoy. A following train has operated by a higher velocity than its leader until the separation distance between them is equal to or shorter than the minimum safe distance.

Quaglietta, Wang, and Goverde (2020) introduced the operational state movement to simulate train operation under the VCS. The VCS will be used when a train approaches a train ahead which will continue on the same route. Both trains will start merged into the same convoy when the separation distance between them becomes shorter than the absolute braking distance. They introduced the estimated braking point ($P_{coupling}$) to indicate the point that a following train should decelerate to be transferred into the convoy state. It depends on the velocity difference between a following train and a train ahead. Thus, a following train will decelerate to be transferred into the convoy state when it is separated from a leading train by $P_{coupling}$. The distance of $P_{coupling}$ is equal to the relative braking distance plus the distance that a following train decelerate from its merging velocity to the same velocity as the front train ($\mathrm{P_{coupling}} = \Delta\mathrm{x}_\mathrm{k}^\mathrm{rel} + \Delta\mathrm{x}_\mathrm{k+1}^\mathrm{re}$). In their proposed state movement, the splitting state is divided into 2 different states: intentional and unintentional splitting. The unintentional splitting is provided to transfer trains being back to the merging state in the case that a following train cannot maintain the distance separated from a leading train.

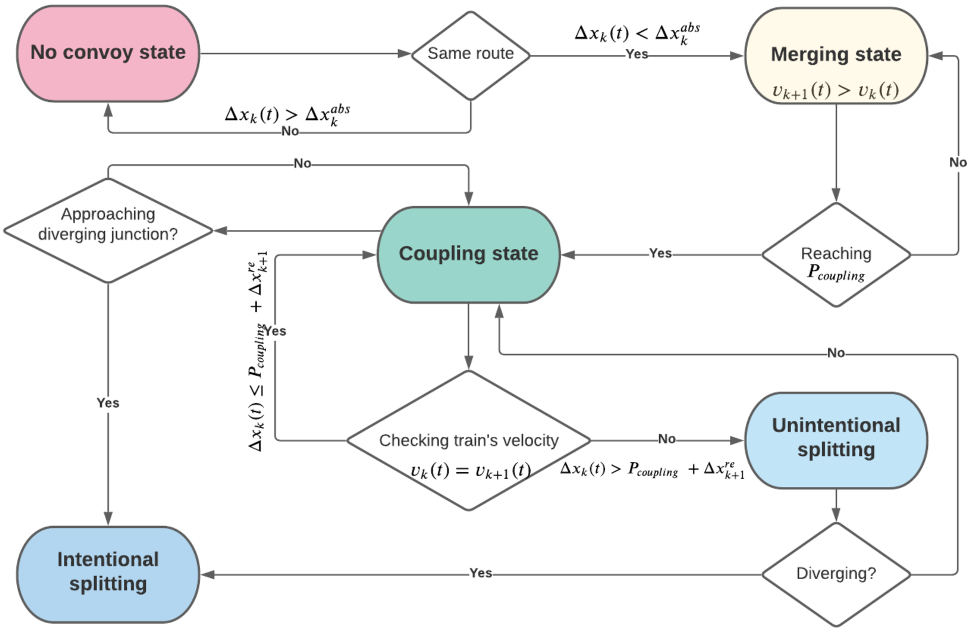


Figure 2.12 State movement for simulating trains under the VCS (Modified from Quaglietta et al. (2020))

Table 2.4 summarizes the previous approaches used to simulating train's movement under both MBS and VCS.

Table 2.4 Summary of previous approaches controlling a train convoy

Authors	Approaches	Detail
K. Li et al. (2005)	If $\Delta x_k(t) > \Delta x_k^{min}(t)$, a train accelerates by a If $\Delta x_k(t) < \Delta x_k^{min}(t)$, a train decelerates by b If $\Delta x_k(t) = \Delta x_k^{min}(t)$, a train operates by constant velocity	▪ The acceleration (a) and deceleration (b) rate is fixed. ▪ $v_{k+1}(t+\Delta t) = \min[(v_{k+1}(t) + a(\Delta t)), v^{max}]$ ▪ $v_{k+1}(t+\Delta t) = \max[(v_{k+1}(t) - b(\Delta t)), 0]$
K. Li and Gao (2007)	$a_{k+1}(t+\Delta t) = u_f f(v) - u_b b(v) - u_h h(d(\Delta x))$ where $u_h h(d(\Delta x)) = [1 + \mathrm{sign}(\Delta x_k(t) - \Delta x_k^{min}(t))]/2$	▪ The acceleration (a) and deceleration (b) are fixed. ▪ u_h , u_f , and u_b refer to an adjustable parameter, the relative traction, and braking force respectively. ▪ $f(v)$ and $b(v)$ are the max. traction and braking force ▪ $u_h h(d(\Delta x))$ is added into the equation to determine the interaction between successive trains
Henke, Ticht, et al. (2008)	Merging state: $v_{k+1}(t) - v_k(t)$ = 2 m/s. if $\Delta x_k(t) > \Delta x_k^{abs}(t)$ $v_{k+1}(t) - v_k(t)$= 0.7 m/s. if $\Delta x_k(t) \le \Delta x_k^{rel}(t) + x_{min}$ Convoy state $v_k(t) = v_{k+1}(t)$ and $\Delta x_k(t) \le x_{min}$ Splitting state: $v_{k+1}(t) - v_k(t)$ = 0.7 m/s. if $\Delta x_k(t) \ge \Delta x_k^{rel}(t) + x_{min}$	The term of velocity difference $(v_{k+1}(t) - v_k(t))$ is used to control velocity of successive trains in the merging state. It is firstly fixed at 2 m/s when the distance between trains is longer than absolute braking distance and then decelerates to 0.7 m/s when the distance between trains is smaller than absolute braking distance.
K. Li and Guan (2009)	$a_{k+1}(t+\Delta t) = C_1[1 - \exp(-C_2\tau)]\left(\frac{1}{\tau}\right)[v^{opt}(\Delta x_k(t)) - v_{k+1}(t)]$	The additional term, $C_1[1 - \exp(-C_2\tau)]$ is added into the traditional optimal velocity car following model for limiting the range of acceleration/deceleration rate and avoiding the collision between trains.

Table 2.4 Summary of previous approaches controlling a train convoy (Continued).

Authors	Approaches	Detail
K.-P. Li et al. (2011)	$a_{k+1}(t+\Delta t) = C_1[1-\exp(-C_2\tau)]\left(\frac{1}{\tau}\right)[v^{opt}(\Delta x_k(t)) - v_{k+1}(t)]$	▪ The term $v^{opt}(\Delta x_k(t))$ is calibrated by adding the coefficient factor (coe) into the traditional equation. It is calculated by $v^{opt}\left(\Delta x_k(t)\right) = \frac{v^{max}}{2}\{\tanh\left[coe * \Delta x_k(t) - \Delta x_k^{min}\right] + \tanh\left[coe * \Delta x_k^{min}\right]$. ▪ The parameter coe is introduced for improving smoothness of velocity profile.
KePing Li and ZiToy Gao (2011)	$a_{k+1}(t+\Delta t) = \left(\frac{1}{\tau}\right)[v^{opt}(\Delta x_k(t)) - v_{k+1}(t)]$ *The optimal velocity term, $v^{opt}\left(\Delta x_k(t)\right)$ depend on the signal status	Green $v^{opt}\left(\Delta x_k(t)\right) = v^{max}$ Yellow $v^{opt}\left(\Delta x_k(t)\right) = \left(v_y - v_r\right)\{\tanh[\Delta x_k(t)]\} + v_r$ Red $v^{opt}\left(\Delta x_k(t)\right) = \frac{v_r}{2}\{\tanh\left[\Delta x_k(t) - \Delta x_k^{min}\right] + \tanh \Delta x_k^{min}$ Where v_y and v_r refer to velocity limit under yellow and red light respectively.
C.-X. Cao et al. (2013)	If $\Delta x_k(t) > \Delta x_k^{min}(t)$, a train accelerates by $a_{k+1}(t+\Delta t)$ If $\Delta x_k(t) < \Delta x_k^{min}(t)$, a train decelerates by $a_{k+1}(t+\Delta t)$ If $\Delta x_k(t) = \Delta x_k^{min}(t)$, a train operates by constant velocity	▪ $\Delta x_k^{min}(t) = [v_{k+1}(t) - v_k(t)]\left(\frac{v_{k+1}(t)}{2a_{k+1}(t+\Delta t)} + \Delta t\right) + sm$ ▪ $a_{k+1}(t+\Delta t) = u_{k+1}(t) - r\left(v_{k+1}(t)\right) + g\left(x_{k+1}(t)\right) - \alpha_{k+1}(t)$ ▪ $v_{k+1}(t+\Delta t) = \min\left[\left(v_{k+1}(t) + a_{k+1}(t+\Delta t)(\Delta t)\right), v^{max}\right]$, and ▪ $v_{k+1}(t+\Delta t) = \max\,[(v_{k+1}(t) - a_{k+1}(t+\Delta t)(\Delta t)), 0]$
J. Ye et al. (2013)	$a_{k+1}(t+\Delta t) = \left[\left(\frac{1}{\tau}\right)[v^{opt}(\Delta x_k(t)) - v_{k+1}(t)]\right] + \lambda\ddot{x}$	▪ Additional term $\lambda\ddot{x}$ is added for determining the velocity difference between successive trains. ▪ $\lambda = 1$ if $\Delta x_k(t) > \Delta x_k^{min}(t)$ and $\lambda = 0$ if $\Delta x_k(t) \leq \Delta x_k^{min}(t)$ ▪ $\ddot{x}$ is related to velocity between two trains $\ddot{x} = -v_{k+1}(t) + \sqrt{v_{k+1}^2 + \frac{1}{M_{k+1}N}\sum_k M_k(v_k'^2 - v_k^2)}$

Table 2.4 Summary of previous approaches controlling a train convoy (Continued).

Authors	Approaches	Detail
Pan and Zheng (2014)	If $\Delta x_k(t) > \Delta x_k^{min}(t)$, a train accelerates by $a_{k+1}(t+\Delta t)$ If $\Delta x_k(t) < \Delta x_k^{min}(t)$, a train decelerates by $b_{k+1}(t+\Delta t)$ If $\Delta x_k(t) = \Delta x_k^{min}(t)$, a train operates by constant velocity	▪ $\Delta x_k^{min}(t) = 0.81(v_{k+1}(t))^2 + (48.72 v_{k+1}(t)) + 281.60$ ▪ $a_{k+1}(t+\Delta t) = (v_k(t) - v_{k+1}(t))/(1.62 v_{k+1}(t) + 48.72)$ ▪ $b_{k+1}(t+\Delta t) = -(v_{k+1}(t))^2/2\Delta x_k(t)$
J. Ye et al. (2015)	$a_{k+1}(t+\Delta t) = \left(\frac{1}{\tau}\right)[v^{opt}(\Delta x_k(t)) - v_{k+1}(t)]$	▪ $v^{opt}\left(\Delta x_k(t)\right) = \frac{v^{max}}{2}\{\tanh\left[\Delta x_k(t) - \Delta x_k^{min}\right] + \tanh\left[\Delta x_k^{min}\right].$ ▪ $\Delta x_k(t)$ is assumed to be an uncertainty factor ▪ $\Delta x_k(t) = \Delta x_{na} + x_{er}$ ▪ Δx_{na} is the actual headway distance between trains ▪ $x_{er} = d_m n_r$ ▪ d_m is the maximum headway distance error ▪ n_r is a random value ranged between -1 and 1

It is noted that the time interval (Δt) should be between 5 to 10 seconds (Farooq & Soler, 2017).

Remark:

$\Delta x_k(t)$ is the separation distance between a leading train (k) and a following train (k+1)

$\Delta x_k^{min}(t)$ is the minimum safe distance between trains

$v_{k+1}(t+\Delta t)$ is the velocity of a following train in the next time step

$a_{k+1}(t+\Delta t)$ is an acceleration/a deceleration rate in the next time step

v^{opt} is the optimal velocity

$\Delta x_k^{rel}(t)$ is the relative braking distance between a leading train (k) and a following train (k+1)

M_k is mass of a train

2.4 Passing a junction

A junction, in a part of railway, is the point that two or more routes diverge or converge. It could be considered as the critical point forcing train to decelerate when approaching due to a lower velocity limit.

2.4.1 Operating passing a junction

The concept of accurate timetable and time keeping is required for managing trains passing through a junction (Connor, 2017). The turnout switch must be clear, set, and completely locked allowing the next train to pass after the front train already passed a junction for ensuring trains could pass a junction safely. It is indicated that at least an absolute braking distance is normally required for installing a junction signal with the ATP in order to ensure that the next train could stop if a junction equipment could not be set for it. In the other words, a turnout switch must be locked at the indicated route before the next train reaches the safe distance (signal) in front of the junction. The signal will inform the driver whether the route is completely set allowing his train to pass and to ensure that there are no other trains passing through a diverging junction (The railway technical website, 2019).

Based on the concept of the VCS, trains will proceed following each other by maintaining safe distance separated from their leading train. Due to short separation distance between successive trains, a higher number of trains could operate along the same route increasing route capacity. However, the route capacity might be lost when a train convoy is approaching a junction (Mitchell, 2016). If any successive trains continue on different routes after passing a junction, the required separation distance between them is normally longer than the minimum safe distance required when they have operated along plain route. It is higher due to switch operation time and a front train length. A train must pass a junction by whole length before allowing a turnout switch equipment set for the next train. As the increase of the separation distance between trains, the number of trains that could pass a junction within defined time is reduced. Thus, the route capacity at a junction is decreased compared to capacity along plain route.

When trains have moved as a train convoy, they have operated by the same velocity for maintaining the distance between them. Then, when they are approaching a junction and will continue on different routes, a following train will decelerate to operate by a lower velocity for lengthening the distance separated from a leading train. It is noted that the separation distance between trains when passing a junction should be close to minimum safe distance at a junction for maintaining the benefit from the VCS.

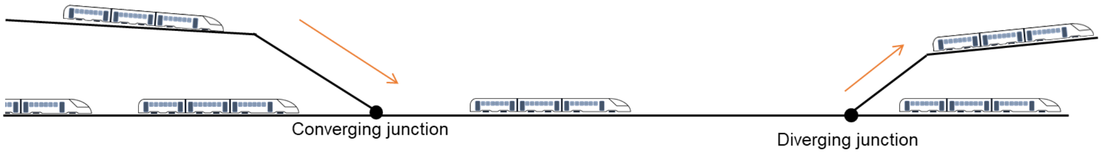


Figure 2.13 Converging and diverging junctions.

Extremely longer separation distance when passing a junction could help trains passing a junction safely but the route capacity will be lost and might result the same as obtained from the main signalling control. So, the question is when a following train should start splitting and how it splits from its leading train?

2.4.2 Controlling trains approaching a junction

A few approaches introduced for controlling a following train movement under the VCS. However, most of them could only be used to simulate a following train proceeding along plain route but the movement of trains when passing through a junction was ignored.

Figure 2.14 shows the movement of a train convoy when approaching a junction. When trains have proceeded along plain route, the minimum safe distance between successive trains basically relies on the relative velocity of both trains and the braking rate of a following train. But when they are approaching a diverging junction, the minimum separation distance required for passing through a junction might be longer due to switch operation time and the leading train’s length. (It might be lower because the velocity limit at a junction is lower than velocity limit restricted along plain route). Thus, a following train must operate by a lower velocity than a train in front to lengthen the distance separated from a front train if the current separation distance between them before passing a junction is shorter than the required minimum safe distance. It is suggested by Mitchell (2016) that the next train should be, at least, at the safe point (absolute braking distance in front of a junction) when the turnout switch is completely locked for the indicated route allowing it to pass. Thus, the minimum safe distance between trains required for passing a diverging junction is equal to the absolute braking distance plus the distance due to the turnout switch operation time and the leading train’s length (**Figure 2.14 (B)**). Similarly, Rabouël, Robin, and Boagey (2011) and Schumann (2017) stated that the minimum safe distance between successive trains when passing a diverging junction relies on the absolute braking distance of a train itself plus the compensated distance due to turnout switch operation time and a leading train’s length.

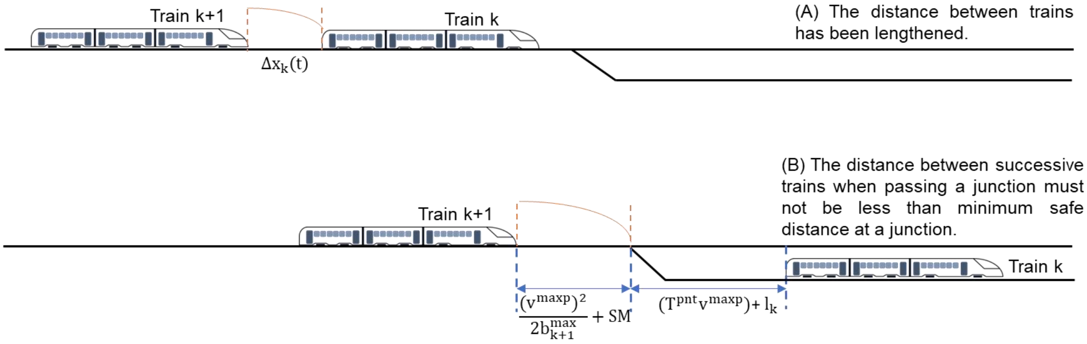


Figure 2.14 Minimum separation distance at a diverging junction (modified from Mitchell (2016))

Quaglietta and Goverde (2019) proposed the equation to estimate the point called “braking indication point”. It is the point that a following train should start slowing down for splitting from its leading train. This point is equal to the absolute braking distance located in front of a diverging junction. It is just the point indicating that a following train should start slowing down but not suggests the optimal velocity that a following train should decelerate to. The distance between trains has been lengthened until it is longer than the minimum safe distance under the MBS that will switch the control back to the main signalling control.

This solution probably works well in the case that there are only two trains virtually coupled as a train convoy. This is because the splitting point is fixed at absolute braking distance in front of a diverging junction. In the case that there are more trains two trains in the same convoy approaching a diverging junction, the trains following the second train may have not enough distance to split out if the second train decelerate to very low velocity for splitting from the first train. For example, a convoy of three trains is approaching the junction and will continue on different routes. The middle train start splitting when reaching the braking indication point by decelerating to very low velocity because of long minimum safe distance required for passing the junction. In this case, the last train will need to decelerate to a lower velocity than the middle train. However, the distance between them might not be able to extend to the safe distance forcing the last train to stop.

At a converging junction, trains that have operated as a train convoy could pass a junction without requirement to split out. They could be judged as a single train. However, they might be required to decelerate for providing appropriate separation distance allowing a train from other routes being inserted into the same route.

2.5 When and how the VCS will be applied?

It is not yet clear exactly when trains should be coupled together as a train convoy. Referring to the previous studies relating to the train's movement under the VCS, only the approaches for controlling trains under the VCS are introduced (C.-X. Cao et al., 2013; K.-P. Li et al., 2011; K. Li & Gao, 2007; K. Li & Guan, 2009; J.-J. Ye & Li, 2013; J. Ye et al., 2013). However, there are a few suggestions describing when the VCS should be used.

According to the approach introduced by Quaglietta and Goverde (2019), the VCS will be applied when a train is approaching a train ahead that will continue on the same route. It means that the signaling control will automatically be changed from the MBS to the VCS when the separation distance between successive trains is shorter than the minimum safe distance under the MBS. However, building a train convoy might not help to increase route capacity if the number of trains operating within the defined time period could not be increased. In addition, building trains as a train convoy may increases travel time especially the front trains in a convoy that basically operate by a lower velocity then their front train through the merging state. Thus, it is important to clear that when trains should be merged together as a train convoy.

Another question is how many trains should be merged into the same convoy? According to the previous studies by C.-X. Cao et al. (2013); Ketphat, Whiteing, and Liu (2020); K.-P. Li et al. (2011); K. Li and Gao (2007); K. Li and Guan (2009); Quaglietta and Goverde (2019a); Xu et al. (2014); J.-J. Ye and Li (2013); and J. Ye et al. (2013), etc, only two trains are built into a train convoy for determining the effectiveness of their proposed approaches. Referring to the simulated results when building a train convoy with different number of trains, it is obviously seen that building more trains into the same convoy increases a longer distance in front of and/or behind the convoy. Building only two trains might result a shorter distance that is not high enough to insert an extra train into the same route. As a result, the route capacity will be the same as route capacity under the main signaling control.

In addition, it is important to know the optimal velocity that a train should proceed for merged into a train convoy. Referring to the simulated results when building a train convoy with different operating velocities, it is found that using a higher velocity difference could help a couple of trains transferred into the convoy state earlier increasing route capacity. However, a leading train maty delay due to a lower velocity that it has proceeded during the merging state. In some previous studies such as the study by Henke and Trachtler

(2013), a train convoy has been built by using fixed velocity difference. As a result, the extended distance after building a train convoy by fixed velocity difference might not be high enough to insert more trains to the same route.

2.6 Parameters affecting route capacity

Each signaling system has its own characteristic that affects the separation distance between trains (Ali, 2016). There are many parameters relating to route capacity such as station spacing, a diverging junction, braking and acceleration rates, etc. (Connor, 2014). Route capacity is related to three terms including technical term, operational strategy, and regulation. The technical term refers to a train’s characteristic, track detail, signalling system and everything in the planning state. The operational strategy relates to passenger demand, frequency of services, and other practical term. The regulations refer to any standards that might be different depending on the policy of each company and an area that a train has passed through.

According to the study by Huayu Duan (2018), it is concluded that both technical and operational strategy terms affect route capacity. Especially the technical term such as braking rate, train length, and operating velocity significantly affects route capacity. The result is similar to the study by Rivera et al. (2020) that is stated that train length, timetable heterogeneity, and braking performance directly affect route capacity.

It is well known that, to obtain the benefit from the VCS, the separation distance between successive trains should be closed to the minimum safe distance as much as possible. Different values of some parameters such as operating velocity, communication time, etc. affect the distance between trains impacting on route capacity.

2.6.1 Operating velocity

Based on the operation under the VCS, minimum separation distance between successive trains is not fixed. It could be changed depending on the real-time data such as operating velocity, braking rate, and safety margin, etc. (Ali, 2016). The operating velocity plays an important parameter in required separation distance between trains. It can be agreed that operating by a higher velocity needs a longer distance to brake (K. Li & Gao, 2007). Abril et al. (2007) stated that route capacity strongly relates to the various parameters especially the operating velocity that directly relates to travel time and the minimum safe distance between trains.

In contrast, proceeding by a higher velocity may increase route capacity because a train needs a shorter travel time allowing a higher number of trains operating within same route (Dicembre & Ricci, 2011). However, if the operating velocity is extremely high, the route capacity tends to be decreased due to a longer minimum safe distance required for separating successive trains. Using a lower velocity requires a shorter separation distance which normally increases route capacity. However, at a lower velocity, other parameters such as train’s length and block section length mainly impact on capacity (Hunyadi, 2011b). Thus, the minimum safe distance between trains could be high although the operating velocity is too low.

K.-P. Li and Fan (2010) studied the impact of operating velocity of low-speed train on route capacity. Their simulated results show that when the operating velocity is greater than 10 km/h, the braking distance is increased mainly depends on operating velocity. However, when the operating velocity is lower than 10 km/h, the required braking distance is also increased due to the impact of other parameters such as braking rate. Similar to the study by Hasegawa, Nicholson, Roberts, and Schmid (2014) which concluded that the minimum safe distance between trains is increased with operating velocity due to a longer distance that the train needs for stopping. But, if a train operates by low velocity (lower than 100 m/s), the headway time is also increased as the decrease in operating velocity. This is because train with a lower velocity will normally brake by using a lower braking rate.

R. Wang, Nie, and Yuyan (2020) studied how operating velocity impact on high-seed route capacity. They found that using a lower velocity results a higher occupation time that could reduce route capacity. Their statement can be agreed by the study by H. Takeuchi, C.J. Goodman, and S. Sone (2003) who studied the route capacity under different types of MBS. It could be summarized that using a higher velocity reduces route capacity due to a longer distance that a train needs to brake. In addition, the capacity is maximized when trains operate under the pure moving block which uses real time velocity to calculate the minimum safe distance.

2.6.2 Braking rate

The braking rate is one important parameter that directly relates to route capacity of both normal and high-speed train (Hunyadi, 2011). It is used to calculate the minimum safe distance between successive trains and to indicate when a following should start decelerates.

As a higher braking rate could reduce the distance separated from a train ahead, route capacity could be increased if a train brakes by using high rate. Braking by using a lower braking rate needs a longer distance to stop. Thus, the distance between trains in increased reducing route capacity.

There are many previous studies determining the impact of braking rate on railway route capacity. For example, H Takeuchi et al. (2003) compared the minimum headway time between trains required under the different types of MBS. The results show the same in all MBS types, in that at the same operating velocity, route capacity is increased with the increase of braking rate. Using a higher braking rate decreases braking distance that a train could stop before colliding with a front train. Similar to the study by Connor (2014), his result could confirm that the braking rate is sensitive to the route capacity. In addition, he suggested that the VCS should be applied for merging trains which have the same braking rate together as a train convoy. Train will have high risk of collision in the case that the braking capability of a following train is lower than its leading train's braking rate. This is because the minimum safe distance under the VCS is calculated from the braking rate of a following train. It is not relied on the braking rate of a leading train. If a leading train brakes by using a higher braking rate than the maximum braking rate of a following train, a following train will has insufficient distance to brake (M. Chen et al., 2020).

2.6.3 Communication time

The train operation under the VCS relies on the communication between train to train for sending and receiving the information between them. Generally, the information such as real-time velocity, position, and route data will be directly sent from a leading train to a following train for calculating the breaking point and to create optimal velocity profile. Thus, route capacity could be increased as a following train can calculate its optimal velocity curve by a train itself. The velocity profile of a following train is more frequently updated in that a following train could decide to move with constant velocity or decelerate. In addition, developing the communication system can improve safety, in which the breaking point (rear of a leading train) could be frequently updated. Thus, the communication time between trains impacts on route capacity, in which, a lower communication time results a higher route capacity (Alikoc, Mutlu, & Ergenc, 2013). Let's imagine that a leading train has moved by a higher velocity than a following train. In case of high communication time, the time that a following train receives a leading train's information to create optimal velocity profile in the next time step is longer. As a result, the distance between trains has been lengthened longer than in the case of low communication time.

Alikoc et al. (2013) said that communication time strongly relates to the actual separation between trains. The distance between trains is quite constant if there is no communication delay. High communication delay requires a longer time, in which a following train spends to adjust its velocity accorded to the distance separated from its front train. The result is similar to the study by R. Chen and Guo (2010). They concluded that using a longer communication time for transferring the data between trains requires a longer separation distance. However, the separation distance might be reduced when the communication time is longer. This is because when the driver spends more time responding to the system, a higher braking rate is required to stop a train. As a result, the braking distance will be decreased. W. Li, Tang, and Liang (2016) studied the impact of communication delay on separation distance between trains under the MBS. They obtained the result that is pretty the same as the studies mentioned above. They found that the separation distance is increased due to the increasing in communication delay. In contrast, the separation distance could be reduced by increasing the communication delay because a train normally uses a lower velocity and brake by using a higher rate when communication delay is high.

2.6.4 Station spacing

Under the FBS, the block section length is fixed limiting route capacity. However, route capacity could be different depending on the length between stations. Francesco, Gabriele, and Stefano (2016) determined the relationship between the length between stations and variability distance between successive trains operating under the FBS. They assumed that trains have operated by the same velocity along the different station spacings. The result shows that the route capacity is increased with the decrease in station spacing. This is because the block length is fixed allowing only one train to be occupied at any one time. A shorter station spacing means a lower number of blocks that a train has passed through. As a result, a higher number of trains could arrive at the next station increasing the route capacity in terms of the number of trains that could operate in an hour. The result is different when trains operate under the MBS. The route capacity tends to be increased with the increase in length between stations. M. Wang et al. (2012) determined the route capacity of different station spacings. But, in their model, mixed types of trains under the MBS are simulated to proceed on the same route. They found that the station spacing impacts on route capacity, in which, for a short station spacing, the route capacity is decreased with the increase of the number of high-speed trains operating along the same route section. This is because a high-speed train could not reach its maximum velocity when following a low-speed train. For long station spacing, the route capacity is decreased with the increase in the number of low-speed trains because they need a longer time to proceed from origin to the next station.

The result is contrary to the result studied by W. Zhao et al. (2014) who studied the impact of station spacing on route capacity with mixed types of trains (low and high speed train) operate under the MBS as well. They concluded that, for short station spacing, the route capacity is increased with the increase of the number of high-speed trains although they could not reach their desired velocity. This is because they will operate by the same velocity and brake by using the same braking pattern as a low-speed train. As a result, the distance between successive trains could be minimized allowing more trains to operate along the same route.

The conclusions above show different results when trains proceed under the VCS. The distance between trains under the VCS not only relies on braking rate and velocity difference between successive trains but also relies on distance between stations. The distance between trains will be decreased with the increase in station spacing as a following train will operate by a higher velocity to catch up with a leading train. A longer station spacing will result higher route capacity because a following train normally needs long distance to catch up with its front train (R. Wang et al., 2020). Schumann (2017) studied the impact of station spacing of high-speed trains operating under the VCS. He concluded that the route capacity is increased with the increase in the length between stations. This is because the high-speed train needs long distance to be coupled into a train convoy. For a short station spacing, the following train might not have enough distance to catch up with a leading train. Thus, the distance between them might be extremely longer than the minimum safe distance reducing route capacity.

2.6.5 Mixed train’s type

Basically, trains which have operated by the same velocity will normally use the same braking pattern. In the case that both low and high-speed trains operate on the same route, the capacity tends to be decreased. This is because when a higher speed train follows a lower speed train, the following high-speed train cannot reach its maximum velocity limiting the performance of high-speed train. In the case that a low-speed train follows a higher speed train, the separation distance between them is extremely long. Thus, the route capacity is decreased (M. Wang et al., 2012).

2.6.6 Junction

The junction is the point that two or more routes diverge or converge, in which the number of trains might be changed after passing a junction. A major problem of operation under the VCS is the decrease of route capacity at a junction. When a train convoy is approaching a diverging junction and two successive trains will continue on different routes, a following train normally operates by a lower velocity than its front train for lengthening the distance between them. To pass a junction safely, the distance between them must be longer than an absolute braking distance plus the distance due to turnout switch operation time (Hunyadi, 2011). The minimum separation distance required for passing a junction is normally longer than the minimum separation distance for plain route due to the time compensated for switching the turnout switch before allowing a train passing (Connor, 2014). Thus, the route capacity under the VCS at the diverging junction will not be different from the capacity under the MBS.

2.6.7 Number of trains

Generally, increasing the number of trains in a train convoy will increase route capacity. The separation distance between successive trains in a train convoy is reduced increasing unused capacity allowing more trains to be inserted to operate along the same route. However, merging more trains into the same convoy could loss the route capacity due to the movement authority calculation time and communication time between trains. Y. Cao, Wen, and Ma (2021) proposed the approach based on leader-follower method to control a set of train convoy. They also study the relationship between number of trains and route capacity. They found that the VCS performance will be lost as the increasing in calculation time. Thus, building more trains into a train convoy could loss route capacity. They suggest that the number of trains in a convoy should not higher than four trains.

2.6.8 Station

Although operating a group of trains as a train convoy could increase route capacity but the route capacity of railway is restricted by station. When the station is occupied by a train, other trains proceeding behind must stop and wait until the front train leaves the station causing low operation efficiency. To maximize route capacity under the VCS, it is important to maximize capacity when a train convoy approaches a station. L. Liu, Wang, Wei, Li, and

Zhang (2019) proposed an intelligent train control under the VCS based on the dispatching and coordinated control method for operating trains approaching a station. The topology network is constructed at the station by assuming the junction and station as a node, and route between adjacent nodes as a segment. The approaching and departing capacity at the high-speed railway station at Nanjing South were simulated. It is found that the approaching and departing capacity based on the proposed approach are increased by approximately 128% and 143% respectively. Not only the number of platform but also the station dwell time impact on route capacity. Longer station dwell time will decrease route capacity in the case that a train proceeds close to its leading train approaching a station. This is due to a higher headway time between two trains, in which the following train may need to stop in front of a station and restart again to arrive at the station (Kunimatsu, Terasawa, & Takeuchi, 2019).

2.7 Limitations of the previous approaches

According to movement of trains under the previous approaches summarized in the **Section 2.3**, there are three conditions that will limit the performance of the VCS. Three shortcomings and the possible causes are summarized below.

2.7.1 Low capacity

According to the simulated train movement under the VCS from some previous approaches, the separation distance between trains when they have operated under the VCS is extremely longer than the minimum safe distance (K. Li & Guan, 2009; Yang et al., 2010; J. Ye et al., 2013). There are three possible causes of low capacity.

First, the cause of high separation distance could be due to long communication and/or evaluation time. Referring to the previous approach based on car-following model, the acceleration and deceleration rate depend on the gap between the separation distance and the minimum separation distance, operating velocity, and the velocity limit. It is not related to the communication time between trains. If the communication time is too long, a following train may operate by a lower velocity than its leading train for a longer time. As a result, the distance between trains may be extremely higher than minimum safe distance. Second, high separation distance could occur when minimum safe distance between trains is fixed. The minimum safe distance should be varied depending on operating velocity, velocity difference between successive trains. However, some approaches use fixed minimum safe distance that is calculated from the velocity limit. Third, it might be due to fixed acceleration/deceleration rate. In some approaches such as the approach introduced by Henke and Trachtler (2013), acceleration and deceleration rate for a following train is fixed. A following train will be forced to decelerate by a fixed deceleration rate although the distance from a train ahead is slightly shorter than minimum safe distance.

2.7.2 Unsafe movement

When trains operate under the VCS, it is important to ensure that the separation distance between successive trains is longer than the relative braking distance. According to simulated results of some previous approaches, it is obviously seen that the distance between some couple of trains is sometime shorter than minimum safe distance (C.-X. Cao et al., 2013; Henke, Ticht, et al., 2008; Henke et al., 2005; J. Ye et al., 2015). As such a situation, a following train may not have enough distance to stop increasing the possibility of collision. There are four possible causes of unsafe situation.

First, it might be due to the condition to transfer trains from merging to convoy state. In some approaches, a following train is stimulated to decelerate to the same velocity as a leading train when the distance between them is equal to the minimum safe distance or is in the range of acceptable safe distance. However, the actual separation distance between trains after transferring into the convoy state is shorter than minimum safe distance due to the different velocity of a couple of trains in the transferring state (K. Li et al.,2005). Second, the distance between trains could be shorter than minimum safe distance because of high braking rate especially the approaches developed from the car-following model. The braking rate of a following train will be high if the current velocity of a following train is largely higher than optimal velocity although the distance from a leading train is close to the minimum safe distance. Using high braking rate will rapidly decrease distance between trains. Thus, separation distance between trains might be shorter than minimum safe distance causing unsafe situation. Third, unsafe situation could be due to fixed acceleration rate. In some approach such as the approach proposed by Henke and Trachtler (2013), a following train is still forced to accelerate by high rate although the distance separated from a leading train is slightly higher than minimum safe distance. Last, the distance between trains could be shorter than minimum safe distance if a following train cannot brake by the required braking rate. In the other words, the unsafe situation could occur if the maximum braking rate is lower than calculated braking rate (K.-P. Li et al., 2011; J. Ye et al., 2015). Another cause of unsafe situation could be due to a lower braking rate of a following train. In the case that the leading train decelerates, but the braking rate of the following train is fixed at a lower rate, the distance between trains could be shorter than minimum safe distance increasing the possibility of collision between trains.

2.7.3 Unstable travelling

Referring to the simulated train’s movement in some previous approaches (K. Li & Guan, 2009; J. Ye et al., 2015), It is seen that trains have difficulty to be transferred to the convoy state. A following train’s velocity during transferring state has frequently been changed causing unstable movement.

Unstable travelling could occur because of the transferring condition used in some approaches that will allow a following train to be coupled with a leading train as a train convoy when the actual gap between them is equal to the minimum safe distance. However, it is difficult to adjust distance separated from a front train to be equal to required minimum safe distance. As a result, a following train’s velocity is frequently changed causing unstable movement. Fixed acceleration and deceleration rated used in some approaches could be considered as the cause of unstable travelling. Basically, when trains are transferred into convoy state, a following train will decelerate by low velocity if its current velocity is close to a leading train’s velocity. But, if the deceleration rate is fixed, the distance separated from a front train will be extended longer than minimum safe distance that will force a following train to accelerate. If an acceleration rate is fixed but the distance between trains is slightly longer than minimum safe distance, a following train might be forced to decelerate again for lengthening the distance between trains. As a result, a train could not maintain stable travelling.

Table 2.5 Shortcomings of the previous approaches

Authors	Objectives	Results	Comment
Henke, Ticht, et al. (2008)	Merging, convoying, and splitting a train convoy by using the concept of velocity difference.	The movement authority of a following train has been adjusted depending on the distance separated from a train ahead. The distance between them has been stable when trains are in convoy state.	The velocity difference between trains is fixed limiting the performance for building a train convoy. It might not be used well in short station spacing because trains will need long distance for building a convoy.
K. Li and Guan (2009)	Limiting the acceleration and deceleration rate of a train.	Acceleration and deceleration rate of a train are in the limited range. In addition, the distance between trains is higher than the minimum safe distance ensuring safety movement.	The separation distance between trains is extremely longer than the minimum safe distance. This will limit the benefit of the VCS, in which the route capacity could not be significantly increased compared to the main signaling control.
Yang et al. (2010)	▪ Limiting the range of acceleration and deceleration rate. ▪ Improving the train movement stability.	The separation distance between most couple of trains is longer than minimum safe distance. The distance between some couples of trains is lower than safe distance but it is still within acceptable range.	▪ The actual gap between successive trains is extremely longer than the minimum safe distance. ▪ The acc/dec rate is sometime higher than the maximum acc/dec capability

Table 2.5 Shortcomings of the previous approaches (Continued)

Authors	Objectives	Results	Comment
KePing Li and ZiYou Gao (2011)	Using the VCS to control trains for increasing route capacity under the FBS.	▪ The trains can proceed safely reducing the possibility of collision between trains. ▪ Separation distance between successive trains is longer than the safe distance (length of physical block)	A train could not obtain stable travelling due to the frequently change in the acceleration and deceleration rate.
J.-J. Ye and Li (2013)	Minimizing the distance between successive trains and controlling trains to arrive at the destination on-time.	The trains arrive at the next station on-time. The route capacity is increased, in that the separation distance between trains is close to the minimum safe distance.	The separation distance between trains is sometime shorter than the minimum safe distance increasing the probability of collision.

Chapter 3
Methodology

To achieve the objectives of this thesis, the methodology is developed based on the main steps outlined below:

1) Minimum safe distance

- Modifying the equation to calculate the minimum safe distance between trains. The equation is modified by adding an additional term that will force a train to decelerate earlier to ensure that a train could operate safely. This is developed in **Section 3.1**.

2) Controlling trains operating under the VCS (Section 3.2)

- Proposed state movement (**Section 3.2.1**) for building a train convoy (merging state), controlling trains operating as a train convoy, and splitting a train from a convoy when approaching a diverging junction.
- The equation to calculate the optimal splitting point and the approach for controlling a train convoy passing a junction (**Section 3.2.2**).
- The analysis of an effectiveness of the proposed approaches (**Section 3.2.3)**.

3) A guideline for building a train convoy

- Capacity consumption (**Section 3.3.1**)
- Capacity utilization (**Section 3.3.2**)

4) Creating a new timetable to insert more trains

- An approach to plan a new timetable (**Section 3.4.1**)
- The conditions to create a new timetable (**Section 3.4.2**)
    - Estimated reaching time (**Section 3.4.2.1**)
    - Estimated reaching time gap (**Section 3.4.2.2**)
    - Minimum headway time (**Section 3.4.2.3**)
    - Number of trains in a convoy (**Section 3.4.2.4**)
    - Merging patterns (**Section 3.4.2.5**)
    - Optimal merging point (**Section 3.4.2.6**)
    - Optimal merging velocity equation (**Section 3.4.2.7**)

5) VCS applications used in operating state

- Building a train convoy to reduce delay (**Section 3.5.1**)
- Building a train convoy when passing a junction (**Section 3.5.2**)

- Building a train convoy following the planned timetable (**Section 3.5.3**)
- Re-determining a train convoy (**Section 3.5.4**)

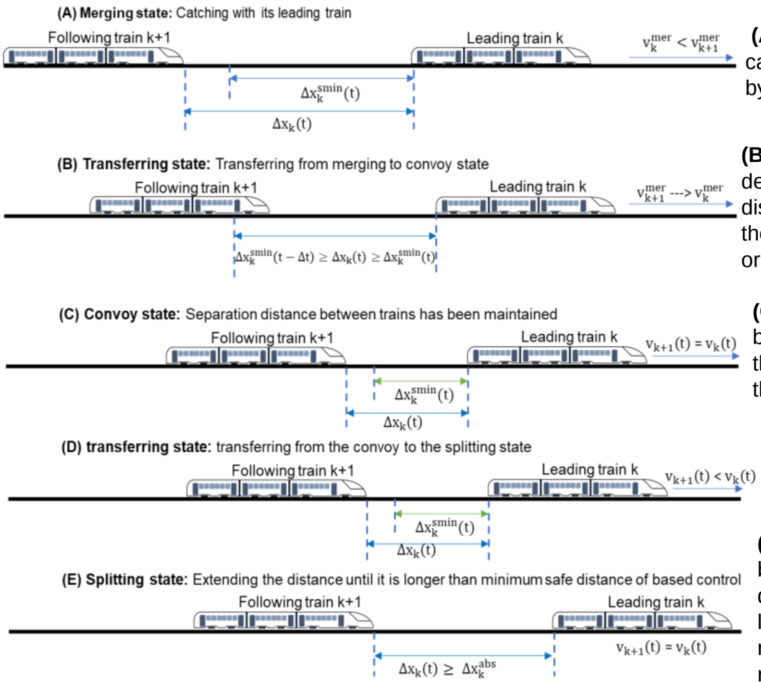
3.1 Modified minimum safe distance under the VCS

In this part, the situations that could cause unsafe situations are explained. An additional term will be added into the traditional minimum safe distance equation to improve safety preventing rear-end collision.

3.1.1 Plain route

Referring the shortcomings of the previous approaches shown in **Section 2.7**, the minimum separation distance could be considered as the possible cause of unsafe movement. To control trains operating safely, the minimum safe distance equation should be modified. The compensated distance (the distance that is added into the minimum safe distance equation to prevent unsafe situation and to ensure that the distance between trains is not shorter than minimum safe distance) is added into the traditional equation. Based on the operation under the VCS, there are three moving states including merging, convoy, and splitting state. Each state will be transferred (transferring state) to another state when a couple of trains meet the conditions of another state. A following train proceeding in each state is described in **Figure 3.1**. A following train has operated by a higher velocity than a leading train for shortening the distance separated from a leading train. It will decelerate to the same velocity as its leading train when the separation distance between them is equal the minimum safe distance or is in the acceptable range of safe distance. It is noted that the minimum safe distance in each state is not equal and could be changed depending on real-time velocities of a couple of trains and the maximum braking rate of a following train.

Unsafe situation may occur during the transferring state where a following train is forced to decelerate to the same velocity as a leading train. The separation distance between successive trains after transferring to the convoy state might be shorter than the minimum safe distance due to different velocities of both trains in transferring state. Thus, to control trains operating safely, the idea is to stimulate a following train to decelerate earlier. The minimum safe distance equation is modified by adding compensated distance to force a following train decelerating to the same velocity as its front train earlier. We now consider the movement behaviour of a following train in two moving states that could lead to unsafe situation. The compensated distance in each moving state will be compared. Then, the highest compensated distance is added into the traditional safe distance equation.



(A) A following train (k+1) is catching up with a leading train (k) by using a higher velocity.

(B) A following train is forced to decelerate when the separation distance between trains is equal to the minimum separation distance or is in acceptable safe range.

(C) Both trains have proceeded by the same velocity maintaining the separation distance between them.

(D) A following train decelerates to a lower velocity than its front train to split out from a train convoy.

(E) A following train has operated by a lower velocity until the distance separated from a leading train is higher than the minimum separation distance required for the main signaling control (MBS).

Figure 3.1 Moving states under the virtual coupling system

3.1.1.1 Transferring from merging to convoy state

Referring to the transferring state from merging to convoy state shown in **Figure 3.1 (B)**, a following train is stimulated to decelerate to the same velocity as its leading train when the distance between them ($\Delta x_k(t)$) is equal to the required minimum safe distance ($\Delta x_k^{min}(t)$). As a result, the distance between trains after transferred into the convoy state will be shorter than minimum safe distance.

At the worst case, if a leading train sends its current position to a following train when a following train reaches braking point, a following train will operate by constant velocity (a higher velocity) for Δt before starting deceleration to be transferred to the convoy state. Thus, to avoid the unsafe situation during the transferring state, additional term is added into the traditional minimum safe distance equation (**Equation (2-3)** in **Chapter 2**). The movement behaviour of a couple of trains when they are transferring from the merging to the convoy state is shown in **Figure 3.2**. The current velocity of a leading and a following train in the merging state at the current time t is $v_k(t)$ and $v_{k+1}(t)$ respectively. As the impact of Δt, the different travelling distance between trains at the beginning of transferring state (**Figure 3.2 (A)**) is

$$\Delta x_k^{trnA} = (v_{k+1}(t) - v_k(t))(\Delta t) \tag{3-1}$$

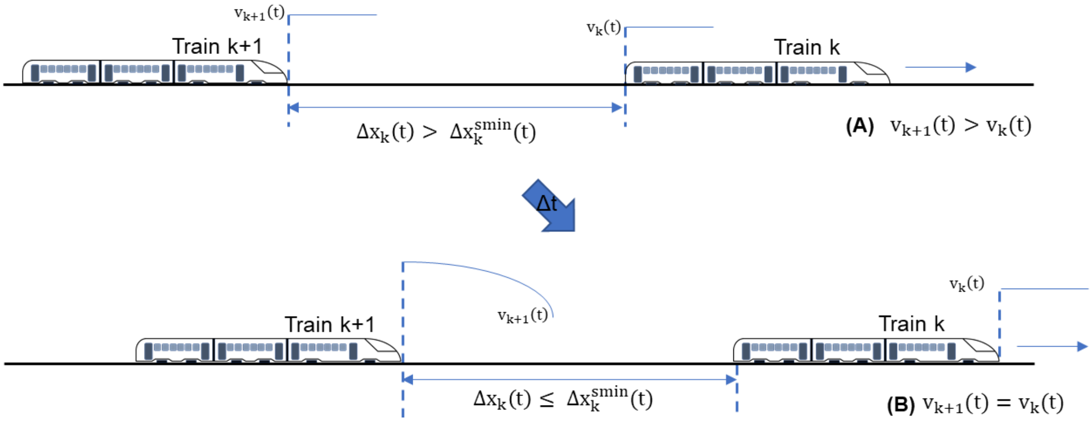


Figure 3.2 Transferring from merging to convoy state

After that (**Figure 3.2 (B)**), a following train will start decelerating to the same velocity as a leading train. The different travelling distance between successive trains in this state (Δx_k^{trnB}) is

$$\Delta x_k^{trnB} = [(v_{k+1}(t))(\Delta t) - 0.5b_{k+1}(\Delta t)^2] - (v_k(t))(\Delta t) \tag{3-2}$$

Where b_{k+1} refers to the optimal braking rate that a following train will apply to be transferred to the convoy state. According to **Equation (3-16),** the equation to calculate optimal deceleration rate, the term of braking rate could be written in terms of velocity ($v_k(t)$ and $v_{k+1}(t)$) and communication time (Δt) by $b_{k+1} = \frac{v_{k+1}(t) - v_k(t)}{\Delta t}$. Placing this term into **Equation (3-2)**, the different travelling distance in this state can be calculated by **Equation (3-3)**.

$$\Delta x_k^{trnB} = \left[(v_{k+1}(t))\Delta t - 0.5\left[\frac{v_{k+1}(t) - v_k(t)}{\Delta t}\right](\Delta t)^2\right] - (v_k(t))(\Delta t) \tag{3-3}$$

The difference of travelling distance between two successive trains during transferred from merging to convoy state is

$$\Delta x_k^{trn} = \Delta x_k^{trnA} + \Delta x_k^{trnB} = 1.5\big((v_{k+1}(t) - (v_k(t))\big)\Delta t \tag{3-4}$$

Thus, the minimum safe distance between trains is modified and can be computed by

$$\Delta x_k^{smin}(t) = \left(\frac{(v_{k+1}(t))^2 - (v_k(t))^2}{2b_{k+1}^{vcs}} + SM\right) + \Delta x_k^{trn} \tag{3-5}$$

It is noted that b_{k+1}^{vcs} is the maximum braking rate that a following could apply to brake. It is the lowest braking rate compared between successive trains. Thanks to the development of the communication system, the trains can communicate and send information to their adjacent trains. The minimum safe distance under the VCS is used. It is calculated using the lowest braking rate, in which $b_{k+1}^{vcs} = \min(b_k^{max}, b_{k+1}^{max})$. When trains have coupled as the same convoy, they could brake by using the same braking rate b_{k+1}^{vcs}. The braking rate of both trains must not be higher than b_{k+1}^{vcs}. Thus, an unsafe situation that a leading train brakes by a higher braking rate is prevented.

3.1.1.2 A leading train decelerates while it is in the convoy state

When a train convoy is in the convoy state, a following train will proceed in relation to a train ahead. However, due to the impact of Δt, a following train could not decelerate instantly although the actual distance separated from a leading train is shorter than minimum safe distance. In the other words, a following train cannot decelerate at precisely the same time as its leading train potentially leading to unsafe situation. The distance between a leading and a following train might be shorter than minimum safe distance especially in the case that the Δt is too long. It could occur if the distance between trains when they have coupled is very close to minimum safe distance.

Assuming that, two successive trains have operated as a train convoy and they have been separated by minimum safe distance (**Figure 3.3**). Thus, the distance between them will be shorter than minimum safe distance instantly after a leading train decelerates. A following train still operates by constant velocity while a leading train decelerate for Δt. As a result, travelling distance of a following train within Δt time period is longer than the distance covered by a leading train. In the worst-case scenario, a leading train decelerates by using maximum braking rate while a following train still operate by constant velocity. The difference of travelling distance between successive trains in this state is

$$\Delta x_k^{conA} = (v_{k+1}(t)(\Delta t)) - \left[((v_k(t))(\Delta t) - \frac{1}{2} b_k^{max}(\Delta t)^2\right] \tag{3-6}$$

In the convoy state, both trains have operated by the same velocity $v_{k+1}(t) = v_k(t)$. Thus, the difference of travelling distance between successive trains under Δt can be calculated by **Equation (3-7)**.

$$\Delta x_k^{conA} = \left[\frac{1}{2} b_k^{max}(\Delta t)^2\right] \tag{3-7}$$

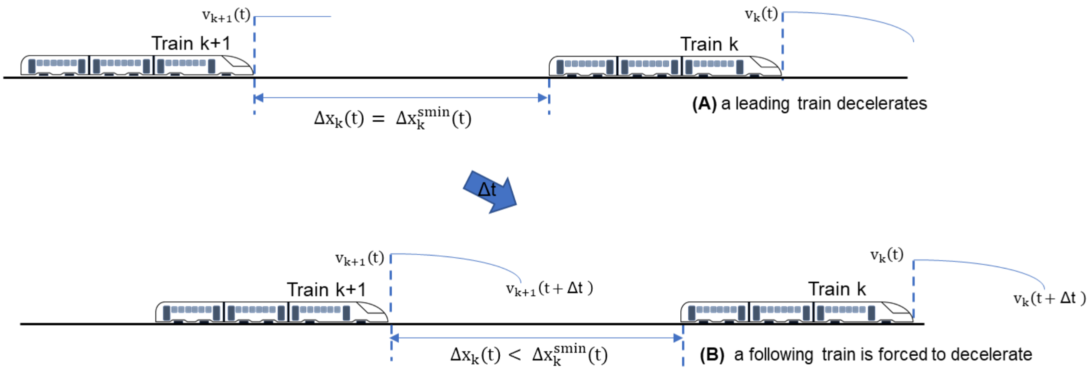


Figure 3.3 A leading train decelerates while it is in the convoy state

Instantly after a leading train decelerates, the separation distance from a following train has been decreased and becomes shorter than the minimum safe distance. Then, a following train will be forced to decelerate to the same velocity as its leading train for maintaining safe distance from a leading train. However, the distance between trains is continuously decreased if a leading train continues to decelerate (**Figure 3.3 (B)**). The problem is we do not know the final velocity of a leading train (the velocity that a leading train decelerates to). Assuming that a leading train decelerates by maximum rate (b_k^{max}) until stop. A following train will be forced to decelerate until it stops as well. The velocity of a leading train after decelerating for Δt can be written in terms of a following train's velocity (v_{k+1}^{conA}) by $v_k^{conA} = v_{k+1}^{conA} - b_k^{max}\Delta t$. Thus, the travelling distance between successive trains in this state is

$$\begin{aligned}\Delta x_k^{conB}(t) = &\left[\left((v_{k+1}^{conA})(T)\right) - \frac{1}{2} b_{k+1}^{max}(T)^2\right] \\ &- \left[\left((v_{k+1}^{conA} - b_k^{max}\Delta t)(T)\right) - \frac{1}{2} b_k^{max}(T)^2\right]\end{aligned} \tag{3-8}$$

The term T refers to the total time that a following train has decelerated until stop. It could be calculated by $T = \frac{v_{k+1}^{conA}}{b_{k+1}^{max}}$. It is noted that the maximum braking rate of all trains merged in the same convoy must be the same ($b_k^{max} = b_{k+1}^{max} = \cdots = b_N^{max}$) for preventing unsafe situation in which a leading train decelerates by a higher rate than the maximum braking capability of a following train. therefore, $T = \frac{v_{k+1}^{conA}}{b_k^{max}}$. The difference of travelling distance between successive trains from **Equation (3-8)** is simply calculated by using **Equation (3-9)**.

$$\Delta x_k^{conB}(t) = [b_k^{max}\Delta t]\frac{v_{k+1}^{conA}}{b_k^{max}} = v_{k+1}^{conA}\Delta t \tag{3-9}$$

The compensated distance that should be added into the traditional equation for providing this unsafe situation (Δx_k^{con}) is $\Delta x_k^{conA} + \Delta x_k^{conB}$. Thus, the modified minimum safe distance created for preventing unsafe situation due to deceleration of a leading train when it is in convoy state can be calculated by using **Equation (3-10)**.

$$\Delta x_{k}^{smin}(t) = \left(\frac{(v_{k+1}(t))^2 - (v_k(t))^2}{2b_{k+1}^{vcs}} + SM\right) + \Delta x_{k}^{con} \tag{3-10}$$

Where $\Delta x_{k}^{con} = \Delta x_{k}^{conA} + \Delta x_{k}^{conB} = \left[\frac{1}{2} b_{k}^{max}(\Delta t)^2\right] + v_{k+1}^{conA}\Delta t$

The extra terms, Δx_{k}^{trn} and Δx_{k}^{con} in two unsafe situations are compared in order to determine the possible worst case. It is found that the compensated distance in the second situation (**Section 3.1.1.2**) is higher possibly causing a higher risk. Thus, the minimum safe distance is modified and can be calculated by **Equation (3-10)**. Thus, a following train will be stimulated to decelerate earlier when it reaches the optimal braking point (**Figure 3.4**) in order to ensure that the distance separated from a leading train is longer than the minimum safe distance (Δx_{k}^{min}).

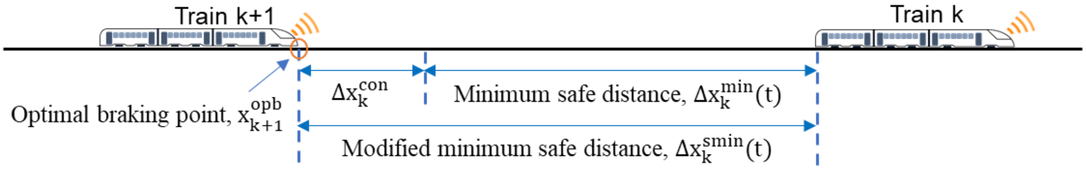


Figure 3.4 Optimal braking point (x_{k+1}^{opb})

Example 3-1: two trains have merged into the same train convoy. The leading and the following train have operated by 55 m/s and 60 m/s in the merging state. Assuming that the maximum braking rate of the following train is 0.5 m/s^2 and the processing time is 10 sec. The safety margin between them is assumed to be 2000 m.

By using the **Equation (3-10)**, the minimum separation between trains ($\Delta x_{k}^{smin}(t)$) is 2650 m (with 75 m compensated distance (Δx_{k}^{con})). In this case, a following train will start decelerating to be transferred into the convoy state when reaching the optimal braking point, 2650 m away from the rear of a leading train.

3.1.2 Converging junction

At a converging junction, a train from other routes will be inserted into the same route via this point. The turnout switch must be set for the converging route before allowing an inserted train to pass. It will be switched back for a train on the main route after an inserted train passing a junction by whole length. Thus, the minimum safe distance between an inserted train and a train on the main route is equal to the absolute braking distance plus the distance due to turnout switch's operation time ($\mathrm{T}^{\mathrm{pnt}}$) and a leading train length (l).

In the case that trains built into the same train convoy pass through a converging junction, a following train is not forced to decelerate to lengthen the distance separated from a leading train. It is only forced to decelerate if its current velocity is higher than velocity limit at a junction. Thus, the minimum safe distance required if successive trains continue on the same route is the minimum safe distance required along the plain route (**Equation (3-10)**). **Figure 3.5** illustrates the movement behavior of trains when passing through a converging junction. It is suggested that the first train in a train convoy must decelerate to $\mathrm{v}^{\mathrm{maxp}}$ (or lower) before reaching the beginning of safe zone (absolute braking distance in front of a junction). When it reaches the safe zone, it is important to check whether the turnout switch is completely locked allowing the next train to pass. If not, a train needs to apply the brake to stop before reaching a junction.

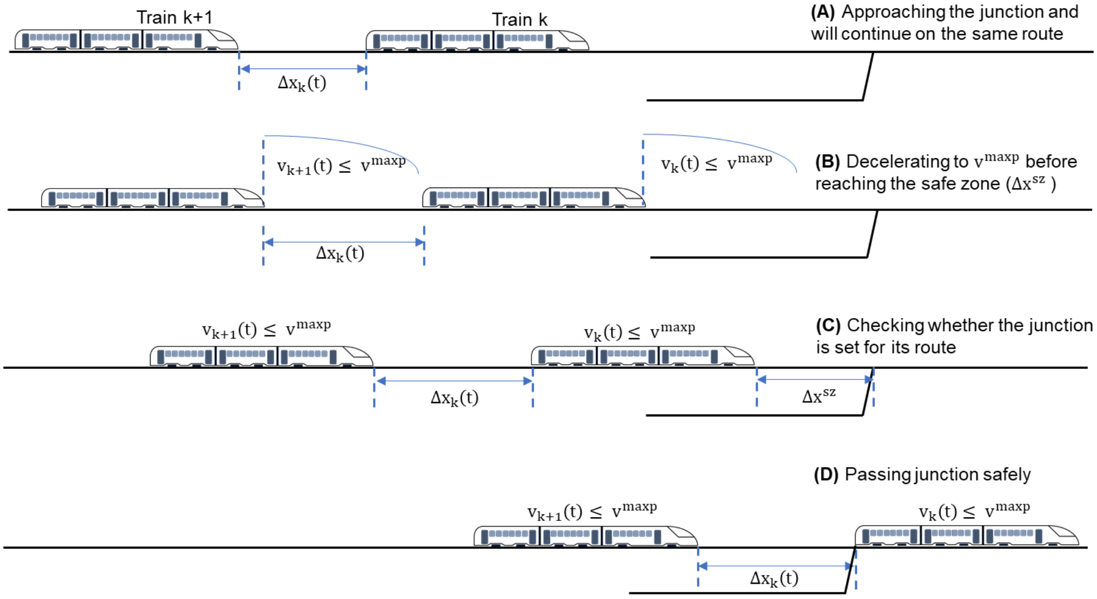


Figure 3.5 Approaching a converging junction

3.1.3 Diverging junction

Figure 3.6 shows the movement of a train convoy when passing through a diverging junction. When a train convoy is approaching a junction and successive trains will continue on different routes, the distance between trains must be extended to, at least, the minimum safe distance. After extending the distance between trains, they must decelerate if their current velocity is still higher than velocity limit at a junction. A following train should be theoretically at the beginning of the safe zone when the turnout switch is completely set at the indicated route (**Figure 3.6 (D)**). Thus, the turnout switch operation time

(T^{pnt}) and a leading train length (l_k) impact on the safe distance between trains a diverging junction. The minimum safe distance at a diverging junction (Δx_k^{mdvr}) can be computed by **Equation (3-11)**.

$$\Delta x_k^{mdvr} = \left(\frac{(v^{maxp})^2}{2b_{k+1}^{max}} + SM\right) + (T^{pnt}v^{maxp}) + l_k \tag{3-11}$$

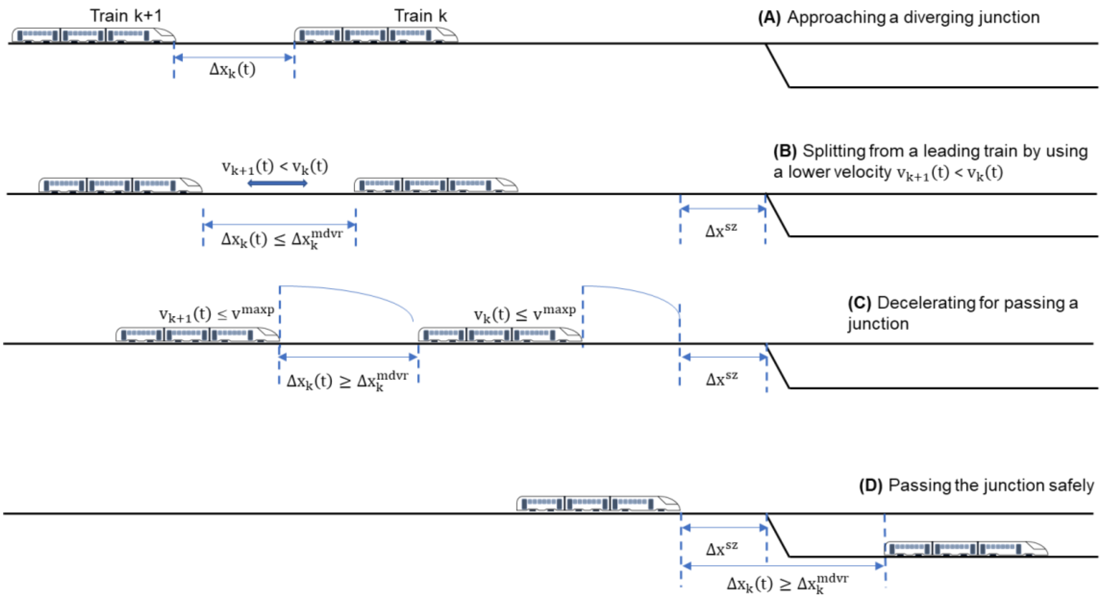


Figure 3.6 Approaching a diverging junction

The equations used to calculate the minimum safe distance at different positions are summarized in **Table 3.1**.

Table 3.1 Minimum safe distance required at different positions

Positions	Equations	Equation No.
Plain route	$\Delta x_k^{smin}(t) = \left(\frac{(v_{k+1}(t))^2 - (v_k(t))^2}{2b_{k+1}^{vcs}} + SM\right) + \Delta x_k^{con}$	(3-10)
Converging junction		
1. Successive trains on the same route	$\Delta x_k^{mcvr} = \Delta x_k^{smin}(t)$	(3-10)
2. Inserted behind a faster train	$\Delta x_{k,m}^{mcvr} = \left(\frac{(v^{maxp})^2}{2b_m^{max}} + SM\right) + (T^{pnt}v^{maxp}) + l_k$	(2-4)
3. Inserted in front of a faster train	$\Delta x_{m,k}^{mcvr} = \left(\frac{(v^{max})^2}{2b_k^{max}} + SM\right) + (T^{pnt}v^{max}) + l_m + \Delta x_m^{cps}$	(2-6)
Diverging junction	$\Delta x_k^{mdvr} = \left(\frac{(v^{maxp})^2}{2b_{k+1}^{max}} + SM\right) + (T^{pnt}v^{maxp}) + l_k$	(3-11)

3.2 Controlling trains under the VCS

According to the shortcomings summarized in **Section 2.7**, the cause of exceeding separation distance and unstable travelling might be due to the state movement or conditions controlling trains transferred to another state. To control the separation distance between trains and to improve movement stability, the state movement for controlling trains operating under the VCS is proposed.

3.2.1 State movement under the VCS

Before operating under the VCS, trains have operated independently under the MBS, in which the distance between successive trains is at least the absolute braking distance.

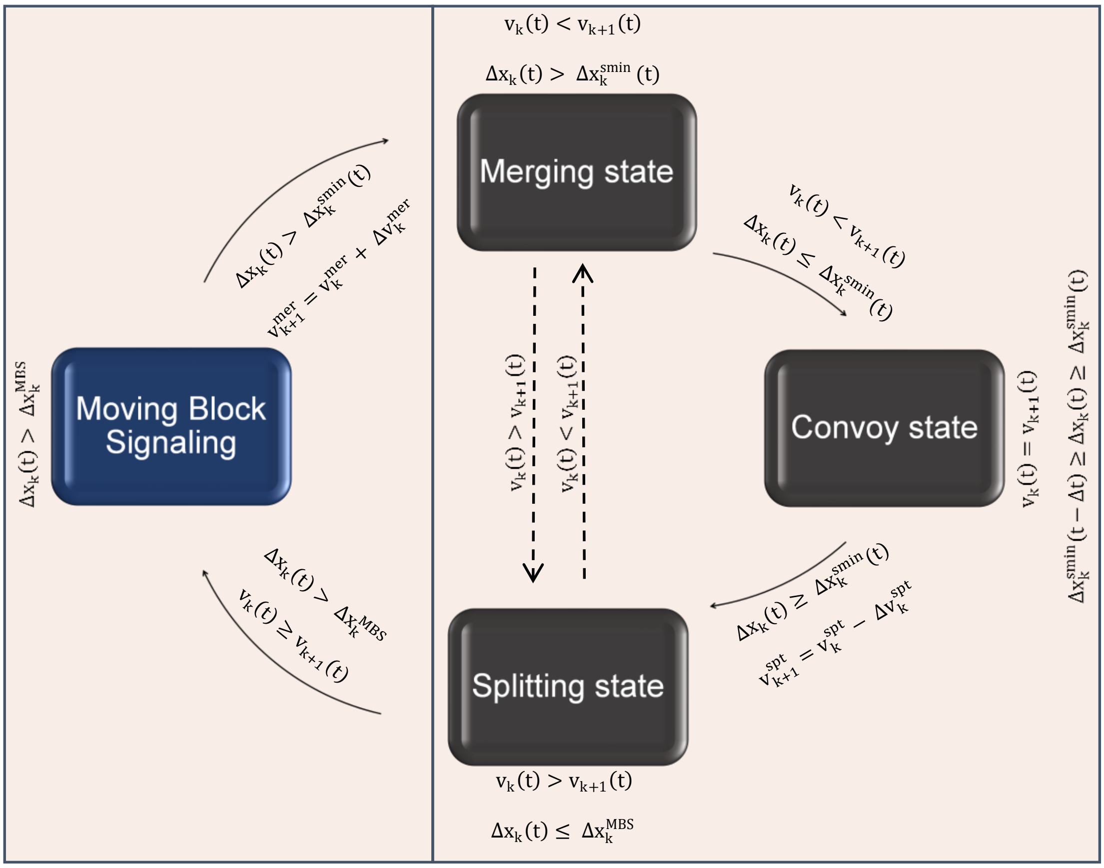


Figure 3.7 Transition between MBS and VCS

In this thesis, an approach for controlling trains operating under the VCS is proposed (**Figure 3.7**). It is developed based on the laws of distance and velocity difference. The signalling system will be switched from the MBS to the VCS when the distance between trains is shorter than the absolute braking distance. It will be transferred from the VCS to the MBS when the distance between successive trains is longer than the absolute braking distance. When trains have operated under the VC, there are three states including merging, convoy, and splitting state.

3.2.1.1 Merging state

Suddenly after being switched from MBS to the VCS, a following train has to adjust its velocity ready to be merged into the same convoy with a train in front. A following train proceeds by a higher velocity than a leading train's velocity for reducing the distance between them. The different velocities between successive trains (Δv_k^{mer}) called "merging velocity gap" should be fixed for ensuring that trains could be transferred into the convoy state within the merging distance. A leading train could maintain its velocity, or either accelerate or decelerate to its merging velocity (v_k^{mer}). The merging velocity of a following train (v_{k+1}^{mer}) could be calculated by

$$v_{k+1}^{mer} = v_k^{mer} + \Delta v_k^{mer} \tag{3-12}$$

It is recommended that a leading train should proceed by constant velocity throughout the merging state to maintain merging velocity gap. If a leading train's velocity is changed while it is in the merging state, the following train's merging velocity will be recalculated by using **Equation (3-12)**. Then, a following train will adjust its velocity in relation to the updated merging velocity of a leading train by using **Equation (3-13)** and **(3-14)**.

$$a_{k+1}^{mer} = \min\left[a_{k+1}^{max}, \frac{(v_{k+1}^{mer} - v_{k+1}(t))}{\Delta t}\right] \tag{3-13}$$

and

$$b_{k+1}^{mer} = \min\left[b_{k+1}^{max}, \frac{(v_{k+1}(t) - v_{k+1}^{mer})}{\Delta t}\right] \tag{3-14}$$

Example 3-2: two trains will start merged into the same convoy by keeping 6 m/s merging velocity gap between them. Assuming that they have operated by the same velocity at 50 m/s before start merged. The maximum braking rate of both trains is 0.5 m/s^2. If the first train's velocity has been kept at 50 m/s through the merging state, the second train's merging velocity will be 56 m/s. With 10 sec processing time, optimal acceleration rate for the following train is 0.5 m/s^2 and 0.1 m/s^2 respectively. It means that the following train will accelerate by 0.5 m/s^2 speeding up from 50 m/s to 55 m/s. Then, it will accelerate again by 0.1 m/s^2 to the target merging velocity at 56 m/s.

3.2.1.2 Convoy state

The modified minimum safe distance calculated from **Equation (3-10)** is set as the acceptable safe distance that a following train uses to decide when it should decelerate to be transferred into the convoy state. When trains are in the convoy state, a following train will accelerate, decelerate, or maintain its velocity to the same velocity as its leading train (See more detail in **Section 3.2.2.1**)

3.2.1.3 Splitting state

Referring to the transition between MBS and VCS shown in **Figure 3.7**, a following train can split out from a convoy by operating by a lower velocity for lengthening the gap separated from a leading train. The splitting state will be completed when the separation distance between trains is longer than minimum safe distance required for the MBS ($\Delta x_k(t) > \Delta x_k^{MBS}$). When trains are approaching a junction, a following train will start split out from a train convoy when it reaches the splitting point (see more detail in **Section 3.2.2.2**).

3.2.2 The approach for controlling trains under the VCS

The approach is developed based on the concept of distance and velocity difference control laws. There are two situations determined; when trains operate along the route, and when they pass a junction.

3.2.2.1 Proceeding along plain route

The state movement conditions in **Table 3.2** is introduced for controlling a following train movement during the merging, transferring, convoy, and splitting state. The aim is to improve train movement stability, to minimize the distance between trains, and to control a following train operating in relation to the movement of a leading train. When trains are in the convoy state, a following train will operate in relation to a leading train movement. It will accelerate if a leading train accelerates, will decelerate when a leading train slows down, and will maintain its velocity if a front train has moved by constant velocity. A following train will adjust its velocity depending on the velocity of a leading train using **Equation (3-15)** and **(3-16)**.

$$a_{k+1}^{opt} = \min\left[a_{k+1}^{max}, \frac{(v_k(t) - v_{k+1}(t))}{\Delta t}\right] \tag{3-15}$$

and

$$b_{k+1}^{opt} = \min\left[b_{k+1}^{max}, \frac{(v_{k+1}(t) - v_k(t))}{\Delta t}\right] \tag{3-16}$$

This ensures that the acceleration (a_{k+1}^{opt}) and deceleration rate (b_{k+1}^{opt}) calculated from these equations do not exceed the maximum acceleration and deceleration rate of a train. It is noted that a following trains might need more than one-time step to adjust its velocity for transferring itself into the convoy state.

Example 3-3: a following train with 0.5 m/s^2 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 (Δt), the optimal braking rate of a following train is $\mathrm{b}_{\mathrm{k+1}}^{\mathrm{opt}} = \min\left[0.5, \left(\frac{(68-60)}{10}\right)\right]$ = 0.5 m/s^2. A following train will firstly decelerate by 0.5 m/s^2 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 $\mathrm{b}_{\mathrm{k+1}}^{\mathrm{opt}} = \min\left[0.5, \left(\frac{(63-60)}{10}\right)\right]$ = 0.3 m/s^2 from 63 m/s to 60 m/s to be transferred into the convoy state.

A following train is forced to accelerate by $\mathrm{a}_{\mathrm{k+1}}^{\mathrm{opt}}$ when the distance separated from a leading train is longer than minimum safe distance and its velocity is higher than velocity of a leading train. This is different from some previous approaches that only focus on the separation distance between trains. A following train is still stimulated to accelerate although its current velocity is already higher than velocity of a train in front.

Table 3.2 Velocity and distance difference control laws under the VCS

State		Distance difference		Velocity difference	Acceleration
1	Splitting state	$\Delta x_k(t) > \Delta x_k^{smin}(t)$	AND	$v_k(t) > v_{k+1}(t)$	a_{k+1}^{opt}
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	Splitting state*	$\Delta x_k(t) \leq \Delta x_k^{smin}(t)$		$v_k(t) > v_{k+1}(t)$	0
5	Transition state*	$\Delta x_k(t) \leq \Delta x_k^{smin}(t)$		$v_k(t) = v_{k+1}(t)$	b_{k+1}^{max}
6	Transition state	$\Delta x_k(t) \leq \Delta x_k^{smin}(t)$		$v_k(t) < v_{k+1}(t)$	b_{k+1}^{opt}

***** The state provided in the case that the distance between successive trains is unintentionally shorter than minimum safe distance.

The control laws in **Table 3.2** could be written as the state movement of trains under the VCS as shown in **Figure 3.8**. The signalling control is changed from the MBS to the VCS when a following train's velocity is adapted to its optimal merging velocity (See more detail in **Section 3.2.1**). After adjusting velocity, a couple of trains will be transferred to be controlled under the VCS in the merging state (**State 3** in **Figure 3.8**).

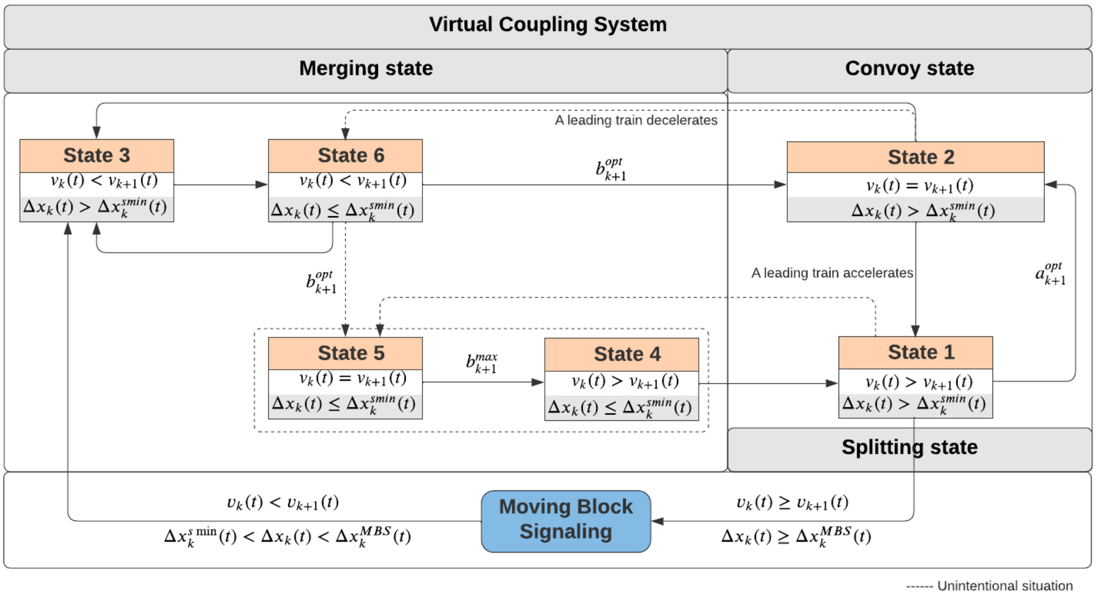


Figure 3.8 State movement of trains under the VCS

Starting with the **State 3** that two successive trains are in the merging state, the separation distance between trains ($\Delta x_k(t)$) is still longer than minimum safe distance ($\Delta x_k^{smin}(t)$) and a following train's velocity is higher than velocity of a train in front. Due to a higher velocity of a following train ($v_{k+1}(t) > v_k(t)$), the distance separated from a leading train has been shortened. Then, the separation distance will be equal to or becomes shorter than the Δx_k^{smin} (**State 6**, transferring state). After that, a following train is forced to decelerate by b_{k+1}^{opt} until $v_{k+1}(t) = v_k(t)$ leading both trains operating under the convoy state. Due to the decrease of a following train's velocity, the minimum separation distance (the relative braking distance) between trains is also decreased.

Example 3-4: two trains have operated by 55 m/s and 60 m/s respectively for merged into the same convoy. In this case, 3550 m minimum separation distance is required in that the following train will decelerate when the distance separated from the leading train is equal to or shorter than 3550 m. After decelerating to the same velocity, both trains will be transferred into the convoy state. The minimum safe distance is updated and changed from 3550 m to 2975 m due to the deceleration of the following train. Thus, the separation distance between trains after transferring into the convoy state is ranged between 2975 and 3550 m.

Thus, it is ensured that the separation distance between trains after transferring to the convoy state is slightly longer than the minimum safe distance (**State 2**). The distance between trains is within the range between the current minimum safe distance ($\Delta x_k^{smin}(t)$) and the minimum safe distance required in the merging state ($\Delta x_k^{smin}(t - \Delta t)$). A couple of trains will be transferred to the splitting state (**State 1**) when a leading train accelerates or when a following train decelerates lengthening the separation distance between them. In this state, 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 decreased due to a higher velocity of a leading train.

A following train can either operates by a lower velocity for splitting out from a convoy (transferred to operate under the MBS) or accelerates by a_{k+1}^{opt} to the same velocity as its leading train and then transferred to the convoy state (**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 required minimum safe distance is increased due to a higher velocity of a following train. In this case, the separation distance between trains after a leading train decelerates is shorter than the minimum safe distance and the velocity of a following train is higher than a leading train's velocity. As a result, a couple of trains will automatically be transferred from convoy state (**State 2**) to merging state (**State 6**). A following train is forced to decelerate by b_{k+1}^{opt} until $v_k(t) = v_{k+1}(t)$ that will transfer a couple of trains operating into the convoy state (**State 2**) again.

It is noted that the **State 4** and **State 5** are provided for avoiding unsafe movement during transferring state. If, after transferred into the convoy state, separation distance between trains is shorter than minimum safe distance, trains will be in the unsafe transition state (**State 5**). In this case, a following train is stimulated to decelerate by maximum braking rate (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 ($v_k(t) > v_{k+1}(t)$) but the distance between them is still shorter than minimum safe distance ($\Delta x_k(t) \leq \Delta x_k^{smin}(t)$). Due to a lower velocity of a following train, the distance away from a leading train is extended until longer than minimum safe distance. Then, a couple of trains will be transferred to the **State 1** that will force a following train to accelerate by a_{k+1}^{opt} for transferred into the convoy state (**State 2**). A following could split out from a train convoy by proceeding by a lower velocity than a leading train. The signalling system will be switched back to the main signalling control when the distance between successive trains is longer than the minimum safe distance required for the main control.

A following train's movement is simulated using the **MATLAB (R2019b)** programming. The coding is built based on the state movement's conditions in **Section 3.2**. It is assumed that trains operate under normal condition with no impact from weather and track elevation.

3.2.2.2 Passing a junction

When a train convoy is approaching a junction and any successive trains will continue on different routes, the distance between the trains must be longer than the minimum safe distance at a junction. The challenge is to identify when a following train should start splitting to obtain safe distance before passing a junction.

1) State movement when approaching a junction

The state movement when a train convoy is approaching a junction is illustrated in **Figure 3.9**. If any successive trains continue on the same route, a following train is not required to split out. They could pass a junction as a train convoy. It is noted that the first train is allowed to accelerate when the last train in a train convoy passed the junction by whole length. Acceleration earlier will force a following train accelerate while it does not pass a junction yet.

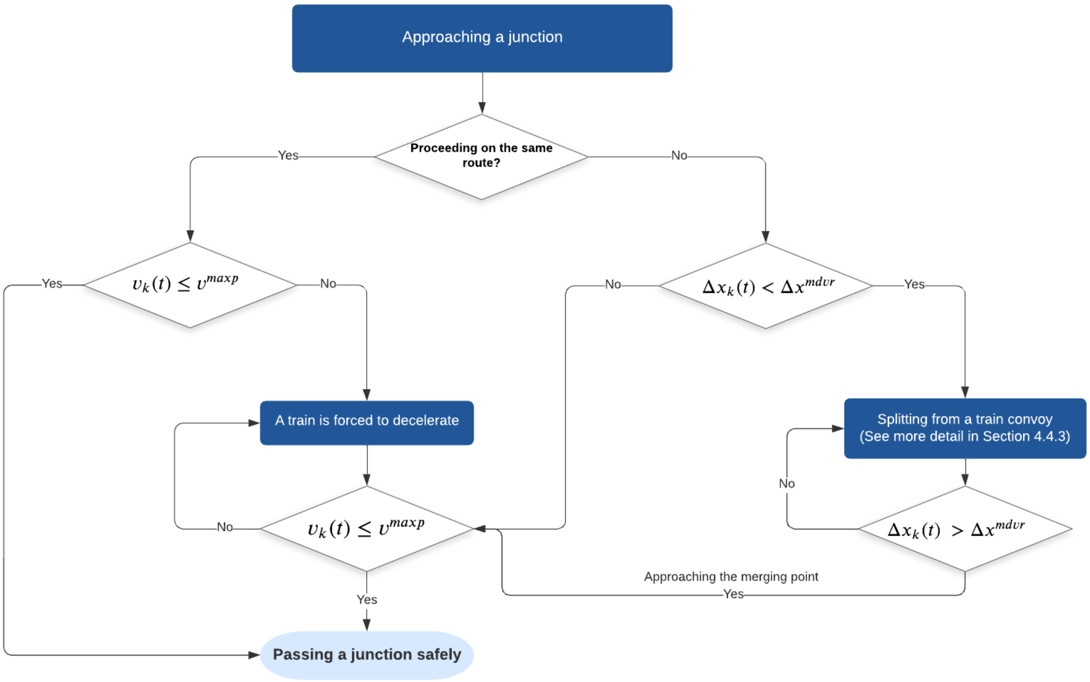


Figure 3.9 State movement for controlling trains passing a junction

A following train will be forced to split out if it and its leading train continue on different routes. It will check the route and prepare to decelerate if its front train continues on different route. It will also send the information to its following train in order to prepare to split out if its following train continue on different routes. Then, a following train needs to check its current distance separated from its front train. It must decelerate to its splitting velocity if the separation distance when reaching the optimal splitting point is shorter than minimum safe distance. A following train will accelerate to the same velocity as its leading train when the separation distance between them is equal to or longer than minimum safe distance at a junction.

The splitting process begins when the first splitting out train reaches the optimal splitting point. For example, fours train are built into the same convoy which is approaching a junction. If the trains 1, 2, and 4 will proceed on route A while the train 3 will continue on route B. The splitting process will begin when the train 3 reaches the optimal splitting point. The trains 3 and 4 will start splitting at the same time.

2) Optimal splitting point

In the proposed approach, the splitting point and length of splitting distance are fixed. The splitting distance refers to the total distance that a following train has proceeded to obtain safe distance for passing a junction. It relies on splitting velocity gap (different velocities between successive trains), and the difference between the distance before splitting and minimum separation distance required for passing a junction. However, the separation distance between trains before splitting is unknown and could be varied. We will consider the worst-case situation, in which the successive trains are separated by only the safety margin. In this case, a following train will need the longest distance for splitting from a train convoy. Thus, it is ensured that a following train can obtain safe distance separated from a leading train before passing a junction.

Referring to the minimum safe distance equation (**Equation (3-10)**), the distance between trains will be minimized when two successive trains operate by the same velocity. Assuming that a train has passed through a junction by $\mathrm{v^{maxp}}$. Thus, the possible minimum distance between trains ($\Delta \mathrm{x_k^{pms}}$) could be estimated by using **Equation (3-17)**.

$$\Delta \mathrm{x_k^{pms}} = \mathrm{SM} + \left(\left(\frac{1}{2} \mathrm{b_k^{max}} (\Delta \mathrm{t})^2 \right) + \mathrm{v^{maxp}} \Delta \mathrm{t} \right) \tag{3-17}$$

Before passing through a junction, the distance between trains is extended from $\Delta \mathrm{x_k^{pms}}$ to the minimum safe distance at a diverging junction ($\Delta \mathrm{x_k^{mdvr}}$). Thus, the distance between them should be extended by

$$\Delta \mathrm{x_k^{exd}} = \Delta \mathrm{x_k^{mdvr}} - \Delta \mathrm{x_k^{pms}} \tag{3-18}$$

It is noted that if the distance between successive trains is longer than the minimum safe distance at a junction. a following train is not stimulated to decelerate for lengthening the distance separated from its front train. It could pass a junction by maintaining the safe distance from it leading train.

Example 3-5 : A couple of trains are approaching the junction (30 m/s velocity limit). With 0.5 m/s^2 maximum braking rate and 2.4 km safety margin, the possible minimum distance between trains is approximately 2.8 km. The distance between trains will be lengthened from Δx_k^{pms} to the minimum safe distance at a diverging junction (Δx_k^{mdvr}) when reaching the safe zone. Thus, the extended distance between successive trains required when approaching a diverging junction (Δx_k^{exd}) is 2.8 m – 2.4 m = 0.4 km.

There are two steps for splitting out from a convoy. First, a following train decelerates to its splitting velocity ($\mathrm{v}_{\mathrm{k+1}}^{\mathrm{spt}}$) which is normally lower than the splitting velocity of its front train ($\mathrm{v}_{\mathrm{k}}^{\mathrm{spt}}$). The estimated time that a following train has covered to decelerate to its splitting velocity is $\Delta \mathrm{t}_{\mathrm{k+1}}^{\mathrm{dec}} = \frac{\mathrm{v}_{\mathrm{k+1}}(\mathrm{t}) - \mathrm{v}_{\mathrm{k+1}}^{\mathrm{spt}}}{\mathrm{b}_{\mathrm{k+1}}^{\mathrm{max}}}$. Assuming that, before splitting, a couple of trains has operated by the same velocity. Thus, the difference of travelling distance of successive trains during the deceleration time of a following train ($\Delta \mathrm{t}_{\mathrm{k+1}}^{\mathrm{dec}}$) is

$$\Delta \mathrm{x}_{\mathrm{k}}^{\mathrm{dec}} = \frac{1}{2} \mathrm{b}_{\mathrm{k+1}}^{\mathrm{max}} \left(\Delta \mathrm{t}_{\mathrm{k+1}}^{\mathrm{dec}}\right)^2 \tag{3-19}$$

Example 3-6 : two trains coupled as the same convoy are approaching the junction at 60 m/s and they will continue on different routes after passing the junction. Assuming that the splitting velocity gap between train is 10 m/s and the maximum braking rate of both trains is equal at 0.5 m/s^2. The following train will firstly decelerate from 60 m/s to 50 m/s by 0.5 m/s^2 taking 20 sec for decelerating. Thus, the travelling distance of the leading and the following train during the same deceleration time period is 1200 m and 1100 m respectively resulting 100 m different travelling distance. It results the same different distance calculated from **Equation (3-19)** in which $\Delta \mathrm{x}_1^{\mathrm{dec}} = \frac{1}{2} 0.5(20)^2 = 100\ \mathrm{m}$.

Second, after adjusting velocity ready to split out, a following train will operate by constant velocity for lengthening the distance separated from the leading train. The different travelling distance in this state can be estimated by using **Equation (3-20)** where Δt_{k+1}^{cst} refers to the total time that the distance between trains has been lengthened to Δx_k^{mdvr}.

$$\Delta x_k^{cst} = (v_k^{spt} - v_{k+1}^{spt})\,\Delta t_{k+1}^{cst} \tag{3-20}$$

The problem is the total time that trains have operated by constant velocity gap (Δt_{k+1}^{cst}) is unknown. However, we know the required extended distance (Δx_k^{exd}, **Equation (3-18)**) and the different travelling distance in the first state (Δx_k^{dec}, **Equation (3-19)**). Thus, the different travelling distance in the second step is

$$\Delta x_k^{cst} = \Delta x_k^{exd} - \Delta x_k^{dec} \tag{3-21}$$

The travelling time that the trains have operated in the second step (Δt_{k+1}^{cst}) can be estimated by using **Equation (3-22)**.

$$\Delta t_{k+1}^{cst} = \frac{\Delta x_k^{exd} - \Delta x_k^{dec}}{(v_k^{spt} - v_{k+1}^{spt})} \tag{3-22}$$

Therefore, the total time that a following train has split from a train convoy is $\Delta t_{k+1}^{dec} + \Delta t_{k+1}^{cst}$. It is suggested that the splitting process should be finished when the first train in a convoy reaches the safe zone. Thus, the length of splitting zone (Δx_{k+1}^{spt}) can be calculated by **Equation (3-23)**.

$$\Delta x_{k+1}^{spt} = v_k(\Delta t_{k+1}^{dec} + \Delta t_{k+1}^{cst}) \tag{3-23}$$

It is noted that the optimal splitting point is calculated for identifying the point that a train should start splitting. In operating state, a train will start splitting when it reaches the fixed splitting point. However, the optimal splitting point could be changed and could be re-calculated depending on the actual distance separated from its front train when it is approaching a junction.

Example 3-7: calculating the optimal splitting point

A couple of trains built as a train convoy are approaching the diverging junction and then will continue on different routes. Both trains have operated by the same velocity at 60 m/s maintaining 3 km separation distance between them. If the minimum safe distance for passing the junction is 3.8 km, the distance needed to be extended before passing the ($\Delta \mathrm{x}_1^{\mathrm{exd}}$) is 800 m. Assuming that the splitting velocity gap is 10 m/s and maximum braking rate of both trains is 0.5 m/s^2. The following train (train 2) will decelerate from 60 m/s to 50 m/s when reaching the splitting point. The total time that the train 2 decelerates to its splitting velocity ($\mathrm{v}_2^{\mathrm{spt}}$) is

$$\Delta \mathrm{t}_2^{\mathrm{dec}} = \frac{\mathrm{v}_2^{\mathrm{opt}} - \mathrm{v}_2^{\mathrm{spt}}}{\mathrm{b}_2^{\mathrm{max}}} = \frac{60 - 50}{0.5} = 20 \text{ sec}$$

The different travelling distance between trains in 20 sec is

$$\Delta \mathrm{x}_1^{\mathrm{dec}} = \frac{1}{2} \mathrm{b}_2^{\mathrm{max}} \left(\mathrm{t}_2^{\mathrm{dec}}\right)^2 = 100 \text{ m}$$

The distance needed to be extended in the next step is

$$\Delta \mathrm{x}_1^{\mathrm{cst}} = \Delta \mathrm{x}_1^{\mathrm{exd}} - \Delta \mathrm{x}_1^{\mathrm{dec}} = 800 - 100 = 700 \text{ m}$$

The total time that trains operate for lengthening the distance for 700 m is

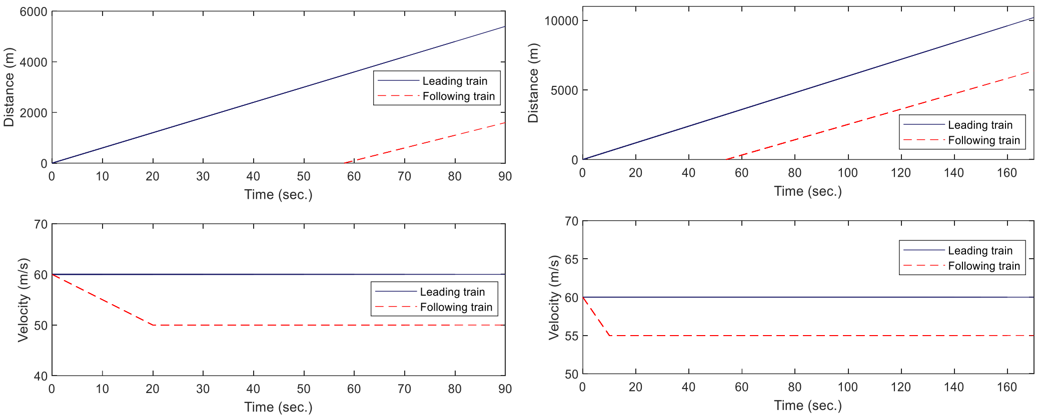
$$\Delta \mathrm{t}_2^{\mathrm{cst}} = \frac{\Delta \mathrm{x}_1^{\mathrm{cst}}}{\left(\mathrm{v}_1^{\mathrm{spt}} - \mathrm{v}_2^{\mathrm{spt}}\right)} = \frac{700}{(60 - 50)} = 70 \text{ sec}$$

Thus, the length of splitting zone with 10 m/s velocity gap is

$$\Delta \mathrm{x}_2^{\mathrm{spt}} = 60(20 + 70) = 5400 \text{ m}$$

It means that the optimal point that the following train should start splitting is approximately 5.4 km from the diverging junction. The simulated distance and velocity profile of trains in this example is shown in **Figure 3.10 (a)**. With 10 m/s splitting velocity gap, the optimal splitting point is 5400 m from the junction. The distance between trains has been lengthened from 3000 m to 3825 m. It results the same splitting distance calculated from **Equation (3-23)**. Thus, it could be confirmed that the proposed **Equation (3-23)** could be used to estimate the optimal splitting point.

Example 3-7 (Cont.): Calculating the optimal splitting point



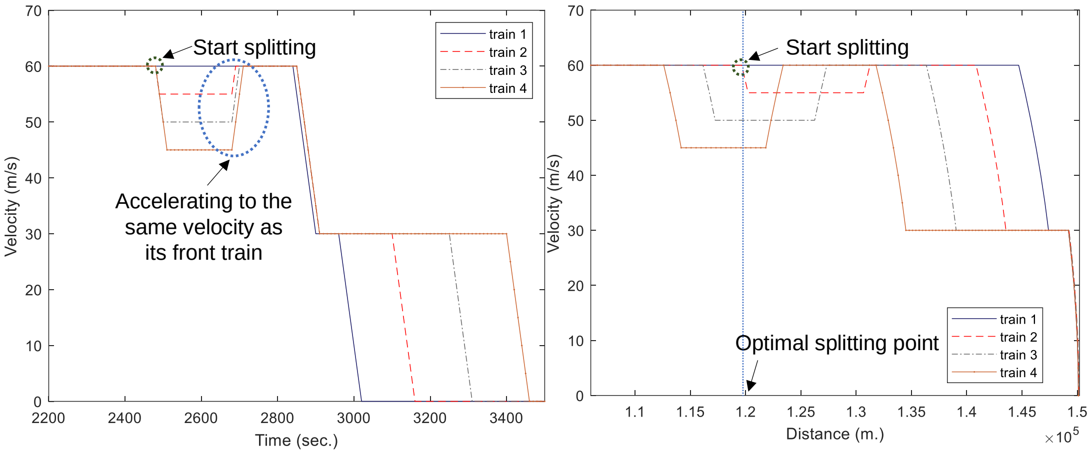
(a) Δv_1^{spt} = 10 m/s

(b) Δv_1^{spt} = 5 m/s

Figure 3.10 Optimal splitting point of different splitting velocity gaps

Figure 3.10 (b) shows the distance and velocity profile when successive trains have split by 5 m/s velocity gap. It is obviously seen that a longer distance is required comparing with the first case. Thus, it can be clearly concluded that a higher velocity gap requires a shorter distance covering to split out from a convoy.

Referring to the previous approaches stated in **Section 2.4.2**, a following train will be forced to decelerate for splitting from a train convoy when it reaches the optimal splitting point which is equal to the absolute braking distance. A train has to operate by a lower velocity until the distance separated from its front train is longer than minimum safe distance at a junction (Quaglietta et al., 2020). It means that if the minimum safe distance is too long but the current separation distance between trains is too short, a following train might have to decelerate to very low velocity. In the case that there are more than two trains merged into the same convoy, if the second train decelerates for extending the distance from the first train, the third train will be forced to decelerate to a lower velocity. It may need to stop to lengthen distance from the second train. Thus, it could be said that the previous approach will be used well only in the case of a few trains built into the same convoy. In the proposed approach, all following trains in the same train convoy will start splitting at the same time. They will start decelerating when first following train (the second train) reaches the optimal splitting point.



(a) Velocity-time profile

(b) Velocity-distance profile

Figure 3.11 Splitting from a train convoy

The **Figure 3.11** shows the distance – velocity profiles in the case that 4 trains have split from the train convoy. Three sub-convoys split out by the the same splitting velocity gap at 5 m/s. The splitting process will begin when the second train (train 2) reaches the optimal splitting point. It will send the information to the trains running behind stimulating them to split out if they continue on the different routes. A train will accelerate to the same velocity as its front train when the distance separated from the front train is longer than minimum safe distance at a junction.

3.2.3 Capacity, safety, and stability evaluation

To determine the effectiveness of the proposed approach, the approach should achieve three conditions including increasing capacity, improving safety, and obtaining stable travelling.

3.2.3.1 Capacity

Basically, capacity in terms of the maximum number of trains in defined time period can be calculated by **Equation (3-24)**.

$$\mathrm{C} = \mathrm{T}/\mathrm{H} \tag{3-24}$$

where T is the time period

H is the minimum headway time

Based on the movement of trains under the VCS, the headway time will be minimized when successive trains operate in the convoy state. Thus, in one hour, the maximum capacity could be calculated by using **Equation (3-25)** where $\Delta t^{\min}$ refers to the minimum headway time between successive trains.

$$\mathrm{C} = 3600/\Delta t^{\min} \tag{3-25}$$

The route capacity in terms of theoretical maximum number of trains under the proposed approach is compared to the maximum capacity under the MBS. The capacity at each point may be different due to different minimum safe distance required when passing each point.

1) Plain route

When trains have operated under the VCS, the first train in any convoy still operates under the MBS. The separation distance between the first train in a convoy and its front train should be at least the minimum permissible headway time required for the MBS (Δt^{MBS}).

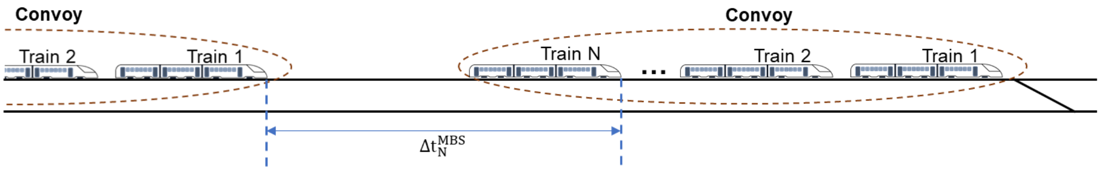


Figure 3.12 Headway time between convoys

The theoretical maximum number of trains operating along the plain route in one hour (C_{pln}^{max}) can be estimated **Equation (3-26)**.

$$C_{pln}^{max} = \frac{3600}{\Delta t^{avr}} \tag{3-26}$$

Where Δt^{avr} refers to average headway time between trains in one hour

2) Converging junction

The theoretical maximum number of trains passing through the junction can be calculated by using **Equation (3-27)**.

$$C_{cvr}^{max} = \frac{3600}{\Delta t_{cvr}^{avr}} \tag{3-27}$$

Δt_{cvr}^{avr} refers to the average headway time between trains when passing a converging junction.

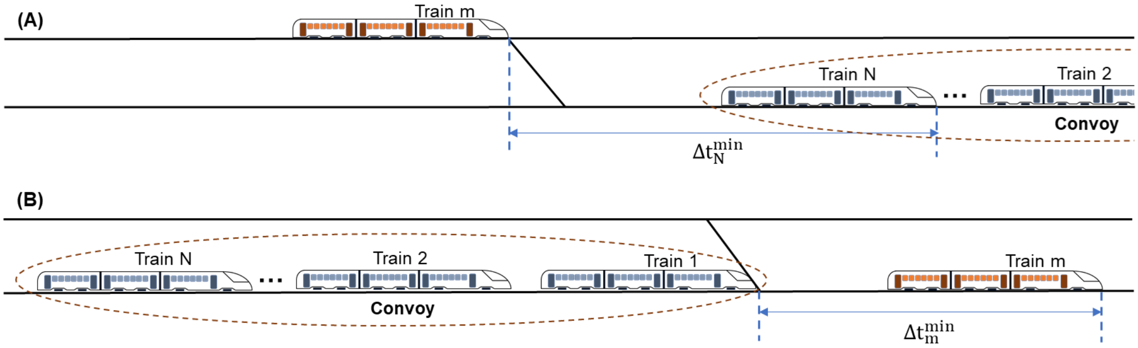


Figure 3.13 Headway time between trains at a converging junction

3) Diverging junction

At a diverging junction (**Figure 3.14**), the last train in a convoy and its following train must be separated by at least the minimum permissible headway time under the MBS (Δt^{MBS}). The maximum number of trains passing through a diverging junction in an hour can be calculated by **Equation (3-28)** where Δt_{dvr}^{avr} refers to the average headway time between trains when passing a diverging junction.

$$C_{dvr}^{max} = \frac{3600}{\Delta t_{dvr}^{avr}} \tag{3-28}$$

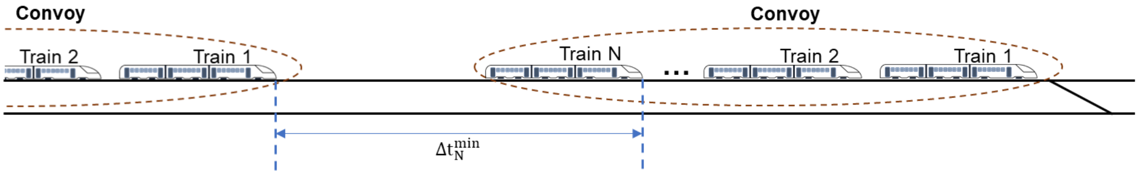


Figure 3.14 Headway time between trains at a diverging junction

3.2.3.2 Safety

1) Separation distance between trains

The proposed approach can be considered as the effective approach if the separation distance between trains when they have operated under the VCS must be higher than minimum safe distance (**Equation (3-29)**) to confirm that trains could operate safely avoiding collision between trains.

$$\Delta x_k(t) \geq \Delta x_k^{smin}(t) \tag{3-29}$$

Also, when trains pass a junction, the separation distance between trains must not be shorter than minimum safe distance required for passing a junction. If successive trains continue on the same route, **Equation (3-29)** is used. If the trains continue on different routes, the distance between trains must not be shorter than minimum safe distance at a diverging junction (**Equation (3-30)**).

$$\Delta x_k(t) \geq \Delta x_k^{mdvr} \tag{3-30}$$

2) Acceleration and deceleration rate

The effectiveness of the proposed approach in terms of safety could also be determined by acceleration and deceleration rate calculated from the approach. These rates must not be higher than the maximum acceleration and braking capability of a train. Thus, it must be in the range between b_{k+1}^{max} and a_{k+1}^{max} (**Equation (3-31)**).

$$b_{k+1}^{max} \leq a_{k+1}(t) \leq a_{k+1}^{max} \tag{3-31}$$

3.2.3.3 Stability

The stability of a train could be determined by using the amplitude of separation distance between successive trains (**Equation (3-32)**). The amplitude of separation distance between trains ($\mathrm{AM_k(t)}$) refers to the difference between the actual separation distance and the minimum safe distance when trains operate under the VCS.

$$\mathrm{AM_k(t) = \Delta x_k(t) - \Delta x_k^{smin}(t)} \tag{3-32}$$

A following train will obtain stable travelling if the amplitude of separation distance through operational time is equal (**Equation (3-33)**).

$$\mathrm{AM_k(t) = AM_k(t + \Delta t) = \cdots AM_k(t + t(end))} \tag{3-33}$$

3.3 Guideline for building a train convoy

To determine how each parameter affects route capacity, both capacity consumption and capacity utilisation should be considered. The capacity consumption is compared to determine the percentage that trains occupy the route. While the capacity utilisation is calculated to identify the why the rate of capacity consumption is different (Landex, Kaas, Schittenheim, & Schneider-Tilli, 2006).

3.3.1 Capacity consumption

The Capacity Utilization Index (CUI) approach which is famously used in UK can be used to calculate the percentage of route capacity consumption (Sameni, Landex, & Preston, 2011). However, the impact of junction or station is not taken into account. The compression method Introduced by UIC 406 (2013) is introduced to eliminate the shortcomings of CUI. It is the ratio of occupied time of compressed timetable to the original timetable.

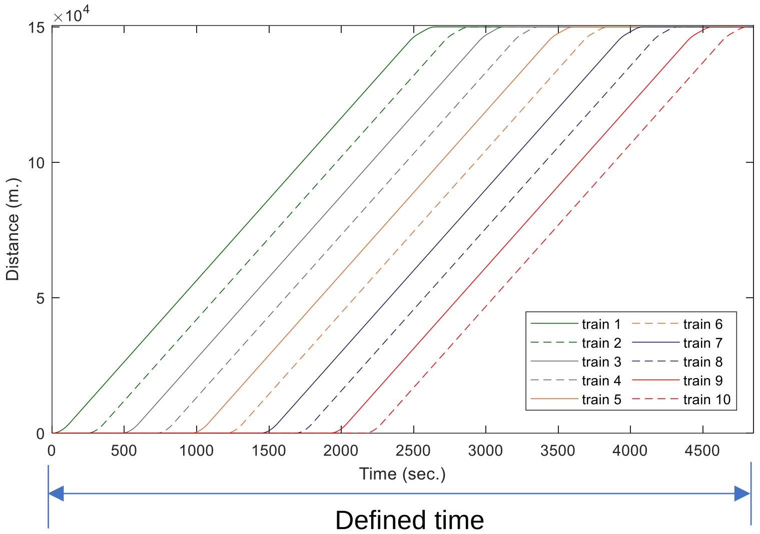
The whole route will be divided into route sections. The route should be divided at junctions, intermediate stations, and the points that the signaling system is changed, etc. The percentage of capacity consumption in each section is compared to find the highest percentage of capacity consumption. The highest one is considered as the representative capacity consumption of the whole route. The capacity consumption (CC) based on the UIC 406 can be calculated by

$$\mathrm{CC\ (\%)} = \frac{\mathrm{OT + AT}}{\mathrm{DT}} \times 100 \tag{3-34}$$

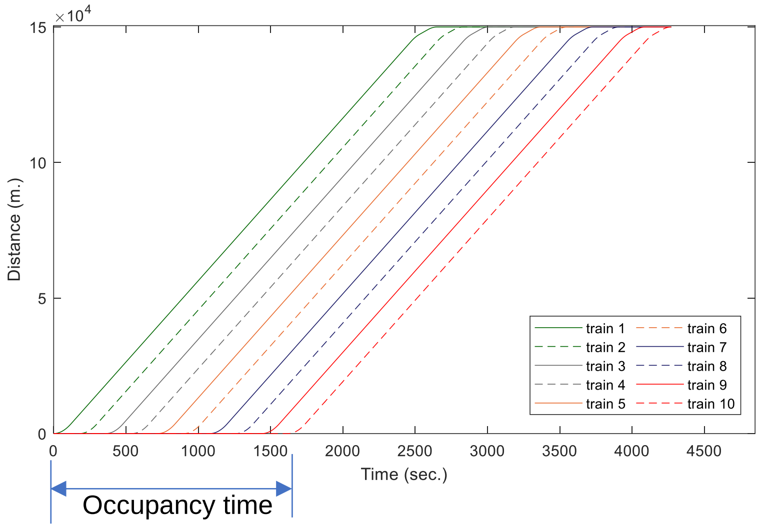
where OT refers to the occupancy time

AT refers to the additional time (buffer time)

DT is the defined time



(a) Before compression



(b) After compression

Figure 3.15 Example of timetable before and after compression (UIC 406, 2013)

According to UIC 406 (2013) compression method, the capacity consumption is calculated only for the defined route sections, not for the whole route. It is suggested that the capacity consumption for the whole route is assumed to be the highest percentage of capacity consumption compared between the defined route sections (Landex, Kaas, Schittenheim, et al., 2006).

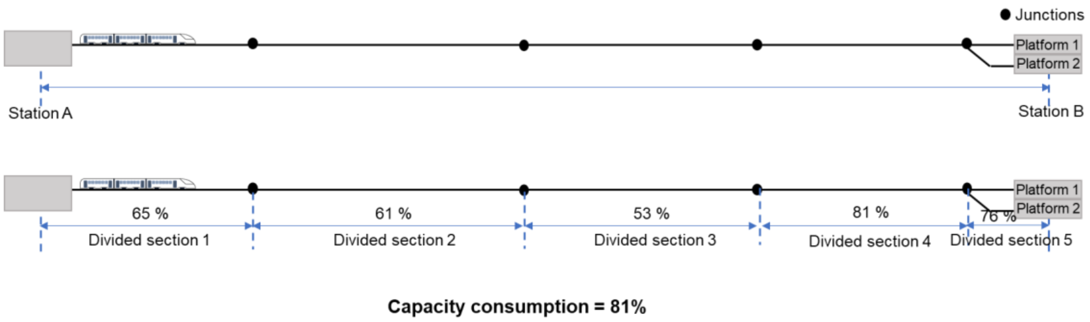


Figure 3.16 Capacity consumption for the whole route

Figure 3.16 shows the example of the calculation of capacity consumption for the whole route. Due to the impact of junction, the rate of capacity consumption is different. As the highest value is considered as the percentage of capacity consumption of the route, the percentage of capacity consumption of this route is 81%.

3.3.2 Capacity utilisation

We know capacity consumption of each route, but we do not know why the rate of capacity consumption could be different. Landex (2007) stated that the term of "Railway Capacity" is a combination of route capacity consumption and utilization. Thus, the possible way to determine why the route capacity is different is to determine the capacity utilisation. As stated in (UIC 406, 2013), capacity theoretically refers to "*the total number of possible paths in a defined time window*". Importantly, not only the number of trains but also other aspects could be used to describe how the route is consumed by trains. The rate of capacity utilization can be determined by four factors including number of trains, velocity deviation, and timetable heterogeneity and punctuality in terms of travel time (**Figure 3.17**). Four aspects should be determined independently for investigating which aspect is the reason of different route capacity.

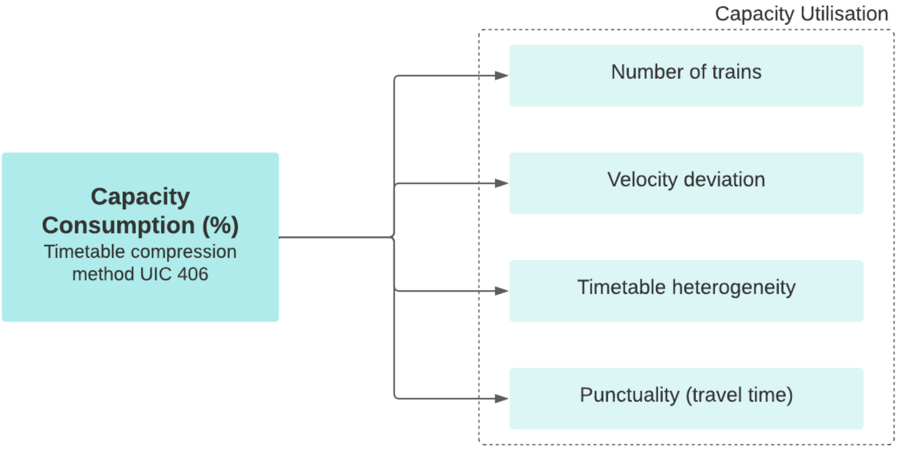


Figure 3.17 Capacity consumption and utilization

3.3.2.1 Number of trains

The maximum number of trains (C_{pln}^{max}) that could operate within the defined time could be calculated by using **Equation (3-26)**. This aspect evaluates the difference between actual number of trains and the maximum number of trains that could operate within the same time period. It is determined based on the assumption that a higher number of trains means a lower rate of unused capacity.

3.3.2.2 Velocity deviation

This aspect is also evaluated based on the assumption that the capacity will be maximized if trains operate by the same velocity. If a train passes a defined point by using a higher velocity, the next train will be allowed to pass the same point faster. As a result, the number of trains that could pass the same point is higher increasing route capacity. However, proceeding by a higher velocity requires a longer braking distance that could reduce the capacity.

In railway operation, the maximum capacity can be obtained when the trains proceed by optimal velocity. If a train operates by a lower velocity than the optimal velocity, the distance separated from a train ahead (operating by optimal velocity) is increased losing capacity (Landex, 2007). Losing capacity could occur when a train proceeds by a higher velocity than the optimal velocity. The distance from its following train that operate by optimal velocity has been increased reducing route capacity. However, it is difficult to measure the loss of capacity. It is suggested that the loss of capacity could be determined via the average deviation (Landex, Kaas, Schittenhelm, & Schneider-Tilli, 2006). The velocity deviation (v_k^{dev}) can be calculated by **Equation (3-35)** where the v_k^{opt} and v_k^{avg} refers to the optimal velocity and the average velocity of the defined train respectively and N is the number of trains within the defined time period.

$$V^{dev} = \frac{\sum_{k=1}^{N} \left| v_k^{opt} - v_k^{avg} \right|}{N} \tag{3-35}$$

3.3.2.3 Timetable heterogeneity

Timetable is homogeneous when the trains operating by the same velocity and stop with the same pattern (**Figure 3.18 (Top)**). Timetable heterogeneity occurs when a following train catches up with a train in front by using a higher velocity or delays resulting the change in the separation distance between two successive trains. As a result, the number of trains operating within the defined time period might be decreased losing capacity

(**Figure 3.18 (Bottom)**). Vromans (2005) proposed the equation to calculate homogeneity of a train timetable as shown in **Equation (3-36)**. Two terms are introduced: the Sum of Shortest Headway time Reciprocals (SSHR) and Sum of Arrival Headway time Reciprocals (SAHR). The proportion of these could be used to explain the spread of trains within the defined time period.

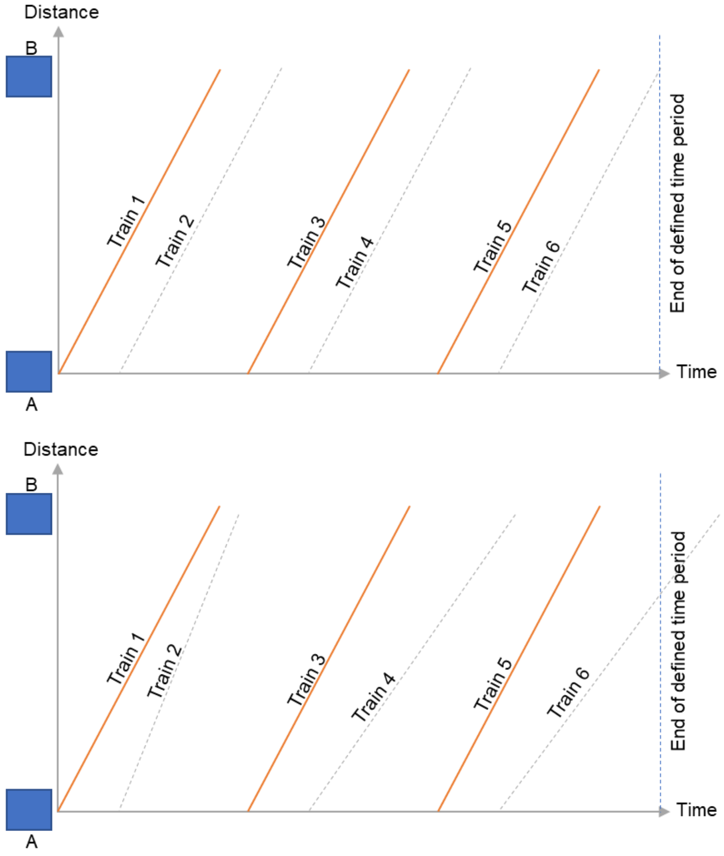


Figure 3.18 Homogeneous (Top) and Heterogeneous timetable (Bottom)

Timetable homogeneity can be calculated by

$$\mathrm{Homogeneity} = \frac{\mathrm{SAHR}}{\mathrm{SSHR}} = \frac{\sum_{k=1}^{n} \frac{1}{\Delta t_k^{arv}}}{\sum_{k=1}^{n} \frac{1}{\Delta t_k^{sht}}} \qquad (3\text{-}36)$$

where Δt_k^{sht} is the shortest headway time between trains

Δt_k^{arv} is the arrival headway time between trains

The homogeneity is ranged between 0 and 1. It is equal to 1 when all trains within the defined time period have proceeded by the same velocity and stop at the next point with the same pattern. In this case, SSHR and SAHR are equal. The homogeneity is converted to the heterogeneity by **Equation (3-37)**. It can be used to describe the spread of trains along the route compared to at the end of the route. A higher heterogeneity means a lower capacity that the route can be utilized.

$$\text{Heterogeneity} = 1 - \text{Homogeneity} \tag{3-37}$$

3.3.2.4 Punctuality

The travel time of a train is determined and used to determine punctuality. The travel time is the total time that a train has moved from origin to destination. It is obtained from the simulation.

3.4 Creating a new timetable: An approach to manage train timetable for inserting more trains

To increase the number of trains operating along the same route, the idea is to build a train convoy to increase the separation distance in front of or behind a convoy allowing more trains to be inserted. The proposed flowchart and the conditions for creating a new timetable are explained below.

3.4.1 An approach for creating a new timetable

We could use the benefit from the VCS to help the planner to create a new train timetable when the number of trains that will operate along the same route is higher than the available capacity under the main control. The flowchart to create a new timetable is proposed as shown in **Figure 3.19**. It starts with the consideration whether a train convoy should be created. Two situations are checked. First, the VCS will be applied to create a train convoy if the number of trains that will operate along the same route exceeds the maximum capacity under the main control. Second, it should be applied when trains from different routes reach the converging junction at almost the same time.

Example 3-8: In 1 hour, there are 15 trains proceeding on the same route approaching the junction where extra three trains from another route will be inserted into the same route. If the maximum capacity under the main signalling control, MBS is 16 trains per hour, the VCS will be applied for creating a train convoy for extending time gap to insert extra three trains.

Second, the next step is to determine a set of involved trains. The estimated reaching time ($\mathrm{T}^{\mathrm{ecv}}$) that a train reaches the converging junction (expected arrival time from the existing timetable) is used to determine which trains should be merged into a train convoy. A train is considered as an involved train and should be merged into a train convoy if estimated headway time (headway time between an inserted train and a train on the main route when passing a junction) is lower than minimum headway time required for passing a junction. A train which will reach a converging junction earlier than an inserted train will be built into a leading convoy. Otherwise, they will be merged into a following convoy.

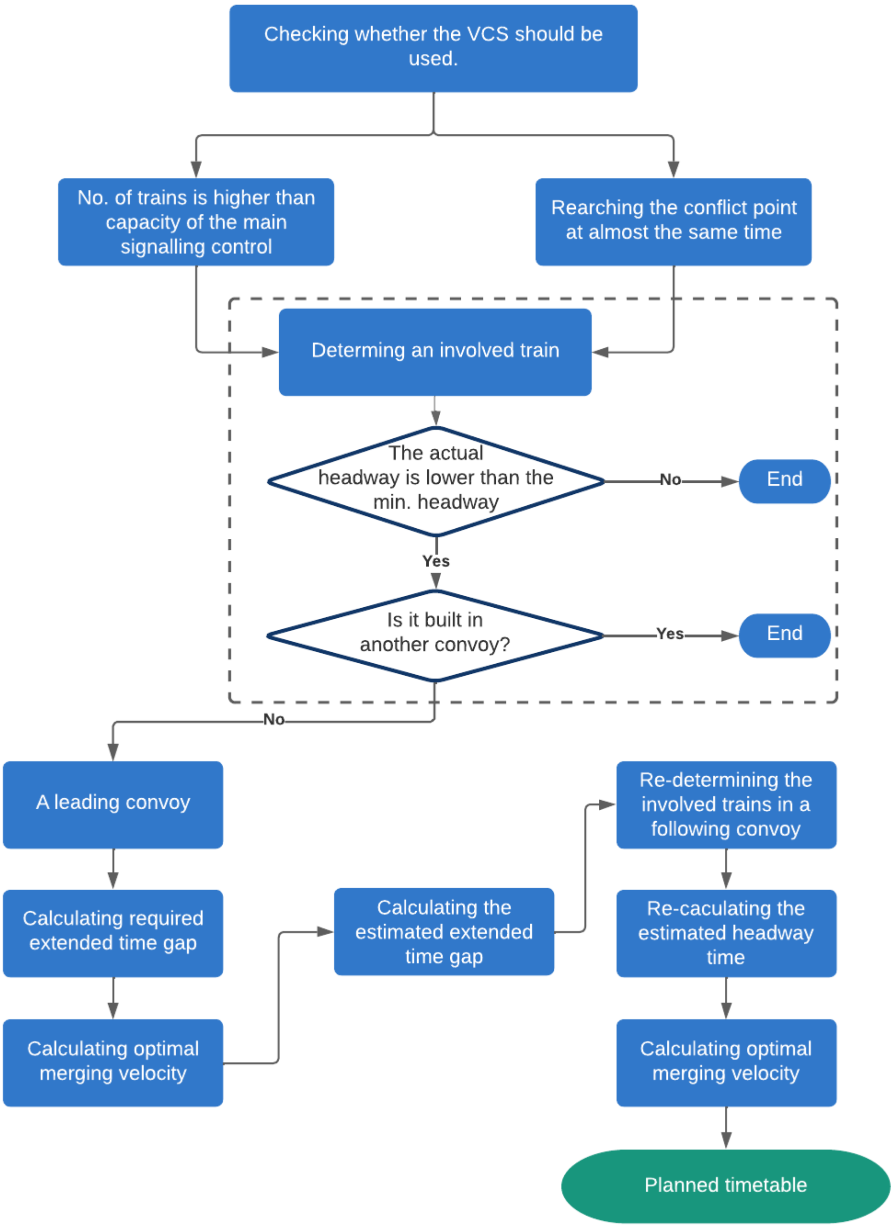


Figure 3.19 The flowchart for creating trains timetable

The next step is to check whether an involved train has already been built into another convoy. It is noted that a train could not be assigned into a new train convoy if it is already built in another convoy. This is because the train will need to adjust its velocity that will impact on the movement of the other trains in the same current convoy. Then, the optimal merging velocity

(v^{mer}) of a train in a train convoy is calculated. The optimal merging velocity is firstly calculated for trains in the leading convoy. This is because their merging velocity is limited due to velocity restriction, in that trains cannot accelerate to a higher velocity (see the merging pattern in **Section 3.4.2.5**). It is noted that the extended time gap obtained from building the leading convoy may be less than the required time gap to insert an extra train. The extended time gap from a leading convoy will be estimated to update estimated reaching time of an inserted train. In the case that the extended time gap obtained after building the leading convoy is lower than the required time gap, the estimated reaching time of an inserted train will be re-arranged.

Example 3-9: The estimated reaching time gap between the last train in the leading convoy and the inserted train is 120 sec. However, at least 180 sec headway time between them is required. After building the leading convoy, the time gap behind the convoy is increased from 120 sec to 150 sec lowering than the minimum time gap at 180 sec. In this case, the estimated reaching time of the inserted train is increased by 30 sec.

Then, after updating the inserted train's estimated reaching time, the estimated headway time between an inserted train and its following trains on the main route is calculated. A train will be merged into the following convoy if its estimated headway time from an inserted train is lower than minimum headway time under the MBS. However, the merging pattern is different, in which the front trains in the following convoy must decelerate and proceed by a lower velocity for extending the time gap in front of the convoy. After that, the optimal merging velocity for trains in the following convoy is calculated. In the last stop, a new timetable is created identifying the trains that should be merged as a train convoy, the number of trains should be built into the same convoy, and optimal merging velocity of all involved trains.

3.4.2 Conditions for creating a new timetable

According to the flowchart in **Figure 3.19**, there are seven terms determined for creating a new timetable.

3.4.2.1 Estimated reaching time ($\mathbf{T^{ecv}}$)

The estimated reaching time (T_m^{ecv}) is the estimated time that a train on the main route reach the converging junction. It could be estimated from the velocity profile of a train based on the existing timetable. The train that will reach the junction earlier than the inserted train will be classified into the leading group (**Equation (3-38)**).

$$\mathrm{T_k^{ecv}} < \mathrm{T_m^{ecv}} \qquad (3\text{-}38)$$

Otherwise, it will be judged as a train in the following group (**Equation (3-39)**).

$$\mathrm{T_k^{ecv}} \geq \mathrm{T_m^{ecv}} \qquad (3\text{-}39)$$

3.4.2.2 Estimated reaching time gap ($\Delta\mathbf{T^{ecv}}$)

The estimated reaching time gap ($\Delta\mathrm{T_{k,m}^{ecv}}$) is the estimated headway time between a train on the main route ($\mathrm{T_k^{ecv}}$) and an inserted train ($\mathrm{T_m^{ecv}}$) when reaching a converging junction. It is calculated by using **Equation (3-40)**.

$$\Delta\mathrm{T_{k,m}^{ecv}} = |\mathrm{T_k^{ecv}} - \mathrm{T_m^{ecv}}| \qquad (3\text{-}40)$$

It will be compared to the minimum headway time ($\Delta\mathrm{T_k^{mcvr}}$) for identifying which train will be built into a train convoy.

3.4.2.3 Minimum headway time ($\Delta\mathbf{T^{mcvr}}$)

To insert an extra train into the main route safely, the reaching time gap between trains from different routes must be at least the minimum headway time required for passing a junction. It is noted that the inserted train is not allowed to be inserted between trains built as the same convoy. It can only be inserted behind or in front of a train convoy. The minimum headway time at a converging junction ($\Delta\mathrm{T_k^{mcvr}}$) can be calculated by using **Equation (3-41)**.

$$\Delta\mathrm{T_k^{mcvr}} = \frac{\Delta\mathrm{x^{mcvr}}}{\mathrm{v^{maxp}}} \qquad (3\text{-}41)$$

(See more detail in the **Section 2.2.2**, minimum safe distance at a converging junction).

3.4.2.4 Number of trains in convoy (N)

The trains that its headway time away from the inserted train is less than the minimum headway time (K trains) will be merged into the same convoy. The number of trains that will be built into the same convoy is calculated by **Equation (3-42)**.

$$\mathrm{N = K + 1} \qquad (3\text{-}42)$$

Another one train is added as the first train in a leading convoy and the last train of a following convoy. It is called the reference train (**Figure 3.20**) provided for preventing delay, in which it will operate by its optimal velocity.

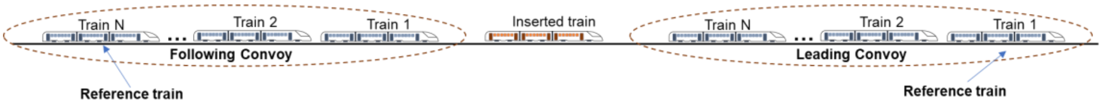
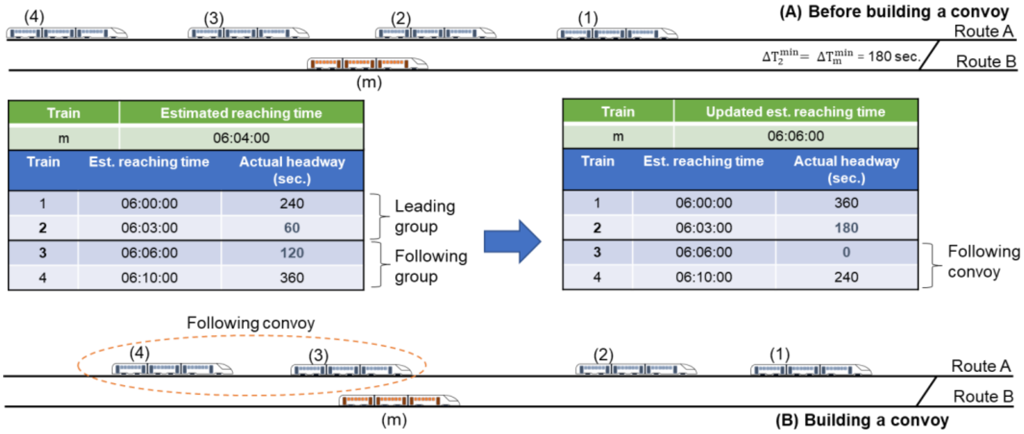


Figure 3.20 Reference train in a leading and a following convoy

Example 3-10: The number of trains in the following convoy

Within a 10 min defined time period, there are four trains proceeding by maximum velocity at 60 m/s along the route A approaching the converging junction. Based on the current timetable, they will reach the junction by estimated time shown in **Figure 3.21**. By comparing their estimated reaching time with the estimated reaching time of the inserted train m, the train 2 should be merged as the same convoy with the reference train 1 for extending the time gap behind the convoy. However, the train 2 could not accelerate to catch up with its leading train because it has already proceeded by maximum velocity. In this case, the leading convoy could not be created. The insert train m should slow down for maintaining safe headway from the train 2. Thus, the estimated reaching time of the inserted train m is updated and changed from 06:03:00 to 06:06:00.



Train	Estimated reaching time	
m	06:04:00	
Train	**Est. reaching time**	**Actual headway (sec.)**
1	06:00:00	240
2	06:03:00	60
3	06:06:00	120
4	06:10:00	360

Train	Updated est. reaching time	
m	06:06:00	
Train	**Est. reaching time**	**Actual headway (sec.)**
1	06:00:00	360
2	06:03:00	180
3	06:06:00	0
4	06:10:00	240

Figure 3.21 Identifying the number of trains in the following convoy

According to the updated estimated reaching time gap shown in the right table in **Figure 3.21**, it is seen that only the time gap between the inserted train m and train 3 is less than minimum headway time at 180 sec. In this case, the train 3 will be built as a following convoy with the reference train 4 for lengthening the distance to insert the inserted train m.

In the case that the extended time gap obtained from the leading convoy is not high enough (lower than the expected time gap), the estimated reaching time gap of the inserted train will be updated by adding the residual time gap (ΔT_{Lead}^{rst}). The updated estimated reaching time of the inserted train can be computed by the equation below.

$$\mathrm{T}^{\mathrm{uecv}} = \mathrm{T}^{\mathrm{ecv}} + \Delta\mathrm{T}_{\mathrm{Lead}}^{\mathrm{rst}} \tag{3-43}$$

3.4.2.5 Merging patterns

The leading convoy is created for lengthening the distance behind the convoy while the following convoy is built to increase the distance in front of it. Thus, the merging pattern of the leading and the following convoy is different.

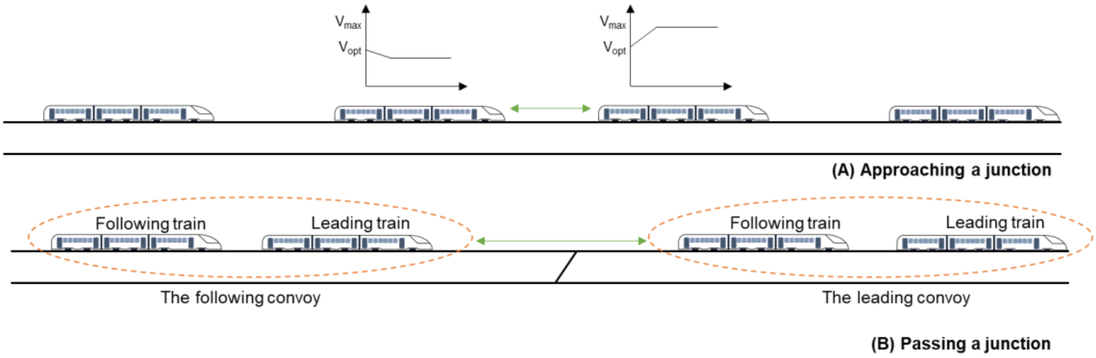


Figure 3.22 Merging patterns of the leading and following convoys

Figure 3.22 shows the merging patterns of a leading and a following convoy. To build a leading convoy, a following train in a convoy will accelerate to a higher velocity than its leading train to catching up with its front train. The convoy proposal including the request to be coupled and a train's data will be sent from a following train to its leading train (**Figure 3.23**).

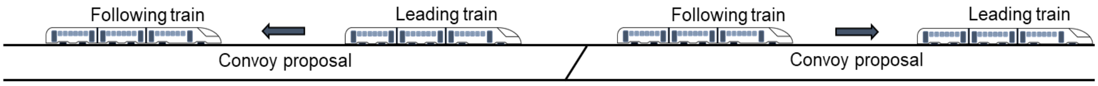


Figure 3.23 Sending the convoy proposal

Note: The **convoy proposal** refers to the request sent to an adjacent train requesting to be merged into the same convoy with the adjacent train.

For a following convoy, a front train in a convoy is stimulated to decelerate for merged with a train running behind for lengthening the distance in front of a convoy. The convoy proposal is sent from a front train to its following train requesting to be merged with the following train.

3.4.2.6 Merging distance ($\Delta \mathrm{x}^{\mathrm{mer}}$)

The merging distance ($\Delta \mathrm{x}^{\mathrm{mer}}$) refers to the distance from the point that a train starts merged into a train convoy ($\mathrm{x}^{\mathrm{mer}}$) to the beginning of the safe zone (The safe zone is equal to the absolute braking distance in front of a junction). The merging distance is fixed at the same point, in that all involved trains should start adjusting velocity to be merged into a convoy when they reach the merging point ($\mathrm{x}^{\mathrm{mer}}$).

3.4.2.7 Optimal merging velocity ($\mathrm{v}^{\mathrm{mer}}$)

The optimal merging velocity for trains in different convoy types could be calculated differently.

1) **Optimal merging velocity for a train in a leading convoy**

A following train must operate by a higher velocity than front train ($\mathrm{v}_1^{\mathrm{mer}} < \mathrm{v}_2^{\mathrm{mer}} < \cdots < \mathrm{v}_\mathrm{N}^{\mathrm{mer}}$) to decrease the distance separated from its leading train. It is recommended that the first train in a convoy (the reference train) should maintain its velocity because we do not need the extended distance in front of a convoy. The time gap in front of the convoy will be increased if the first train proceeds by a lower velocity than its optimal velocity. Thus, we can use the first train's velocity as the reference velocity to calculate the optimal merging velocity for the other trains in the same convoy.

The optimal merging velocity of following trains can be calculated depending on the extra time gap ($\Delta\mathrm{t}_{\mathrm{Lead}}^{\mathrm{ext}}$) required to insert a train(s) from different routes. The extra time gap needed behind a leading convoy (**Equation (3-44)**) can be estimated by comparing the estimated headway time between the last train in the leading convoy and the inserted train ($\Delta\mathrm{t}_{\mathrm{N,m}}^{\mathrm{ecv}}$) with the minimum headway time for passing a junction ($\Delta\mathrm{t}_{\mathrm{N,m}}^{\mathrm{min}}$).

$$\Delta\mathrm{t}_{\mathrm{Lead}}^{\mathrm{ext}} = \Delta\mathrm{t}_{\mathrm{N,m}}^{\mathrm{min}} - \Delta\mathrm{t}_{\mathrm{N,m}}^{\mathrm{ecv}} \tag{3-44}$$

As the trains can pass a converging junction by $\mathrm{v}^{\mathrm{maxp}}$, the extra time gap ($\Delta\mathrm{t}_{\mathrm{Lead}}^{\mathrm{ext}}$) can be converted to the extra separation distance ($\Delta\mathrm{x}_{\mathrm{Lead}}^{\mathrm{ext}}$) by using **Equation (3-45)**.

$$\Delta\mathrm{x}_{\mathrm{Lead}}^{\mathrm{ext}} = \mathrm{v}^{\mathrm{maxp}} \times \Delta\mathrm{t}_{\mathrm{Lead}}^{\mathrm{ext}} \tag{3-45}$$

To build a leading convoy, the last train (N) in a convoy will accelerate to $\mathrm{v}_\mathrm{N}^{\mathrm{mer}}$ while the first train proceeds by $\mathrm{v}_1^{\mathrm{mer}}$ for merged into the same convoy.

As $\mathrm{v}_\mathrm{N}^{\mathrm{mer}} > \mathrm{v}_1^{\mathrm{mer}}$, the distance covering by both trains within the same time period is different. Thus, the total time that both trains proceed for obtaining the extra time gap ($\Delta\mathrm{t}_\mathrm{N}^{\mathrm{mer}}$) is

$$\Delta\mathrm{t}_\mathrm{N}^{\mathrm{mer}} = \frac{\Delta\mathrm{x}_{\mathrm{Lead}}^{\mathrm{ext}}}{(\mathrm{v}_\mathrm{N}^{\mathrm{mer}} - \mathrm{v}_1^{\mathrm{mer}})} \tag{3-46}$$

Assuming that the last train in a convoy will accelerate to its merging velocity when it reaches the merging point, $\mathrm{x}^{\mathrm{mer}}$ (**Figure 3.24**). The total time that the last train ($\Delta\mathrm{t}_\mathrm{N}^{\mathrm{mer}}$) in a leading convoy has proceeded through the merging distance is

$$\Delta t_N^{mer} = \Delta x^{mer} / v_N^{mer} \tag{3-47}$$

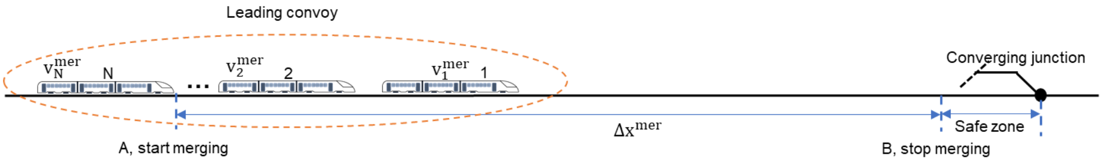


Figure 3.24 Building a leading convoy

Now, we know the merging distance (Δx^{mer}), the extra separation distance (Δx_{Lead}^{ext}), and the optimal merging velocity of the first train (v_1^{mer}). By placing the total time Δt_N^{mer} in **Equation (3-47)** into **Equation (3-46)**, the optimal merging velocity of the last train in a leading convoy (v_N^{mer}) can be calculated by **Equation (3-48)**.

$$v_N^{mer} = v_1^{mer} \Big/ \left(1 - \frac{\Delta x_{Lead}^{ext}}{\Delta x^{mer}}\right) \tag{3-48}$$

However, a train cannot accelerate to velocity higher than the velocity limit (v^{max}) because accident mainly occur due to over speed (H.-E. Liu, Yang, & Cai, 2018). Thus, the term of maximum velocity is added into **Equation (3-48)** for limiting the optimal merging velocity. Thus, the optimal merging velocity of the last train can be calculated by using **Equation (3-49)**.

$$v_N^{mer} = \min\left[v^{max}, \left(v_1^{mer} \Big/ \left(1 - \frac{\Delta x_{Lead}^{ext}}{\Delta x^{mer}}\right)\right)\right] \tag{3-49}$$

If more than two trains are built into the same convoy, the optimal merging velocity of other trains could be estimated by

$$v_{k+1}^{mer} = \max[(v_k^{mer} + \Delta v^{omer}), v_N^{mer}] \tag{3-50}$$

where Δv^{omer} refers to the optimal merging velocity gap between two successive trains. It can be estimated by **Equation (3-51)**.

$$\Delta v^{omer} = \frac{(v_N^{mer} - v_1^{mer})}{K} \tag{3-51}$$

Estimated extended time gap after building a leading convoy

Due to the velocity limit, the extended time gap after building a leading convoy could be less than minimum headway time for inserting an extra train. It is recommended that an insert train should reach the converging junction lately for maintaining safe headway time away from its front train. Thus, the estimated reaching time of the inserted train will be changed. The estimated extended time gap obtained after building a leading convoy (Δt_{Lead}^{etg}) could be estimated by **Equation (3-52)**.

$$\Delta t_{\mathrm{Lead}}^{\mathrm{etg}} = \left(\Delta x^{\mathrm{mer}}\left(1-\frac{v_1^{\mathrm{mer}}}{v_N^{\mathrm{mer}}}\right)\right)\Big/ v_N^{\mathrm{mer}} \tag{3-52}$$

The estimated reaching time of an inserted train (m) is re-calculated (t^{ucv}) and could be updated by using **Equation (3-53)**.

$$t_m^{\mathrm{ucv}} = t_m^{\mathrm{ecv}} + \Delta t_{\mathrm{Lead}}^{\mathrm{rst}} \tag{3-53}$$

where $\Delta t_{\mathrm{Lead}}^{\mathrm{rst}}$ refers to the residual time gap from a leading convoy that could be computed by **Equation (3-54)**.

$$\Delta t_{\mathrm{Lead}}^{\mathrm{rst}} = \Delta t_{\mathrm{Lead}}^{\mathrm{ext}} - \Delta t_{\mathrm{Lead}}^{\mathrm{etg}} \tag{3-54}$$

Example 3-11: Optimal merging velocity of trains in the leading convoy

Within a 15 min defined time period, four trains will operate along the route which has 80 m/s velocity limit. They will be built into the same convoy as the leading convoy to lengthen the distance behind the convoy. Assuming that the train 4 (last train in convoy) accelerates to the maximum velocity for merged into the convoy while the first train operate by constant velocity at 60 m/s. The optimal velocity gap between successive trains is $\Delta v^{\mathrm{omer}} = \frac{(v_N^{\mathrm{mer}} - v_1^{\mathrm{mer}})}{K} = \frac{(80-60)}{3} = 7\ \mathrm{m/s}$. The optimal merging velocity for all four trains in this convoy is

$$v_1^{\mathrm{mer}} = 60\ \mathrm{m/s}$$

$$v_2^{\mathrm{mer}} = \max[(v_1^{\mathrm{mer}} + \Delta v^{\mathrm{omer}}), v_4^{\mathrm{mer}}] = \max[(60+7), 80] = 67\ \mathrm{m/s}$$

$$v_3^{\mathrm{mer}} = \max[(v_2^{\mathrm{mer}} + \Delta v^{\mathrm{omer}}), v_4^{\mathrm{mer}}] = \max[(67+7), 80] = 74\ \mathrm{m/s}$$

$$v_4^{\mathrm{mer}} = \max[(v_3^{\mathrm{mer}} + \Delta v^{\mathrm{omer}}), v_4^{\mathrm{mer}}] = \max[(64+7), 80] = 80\ \mathrm{m/s}$$

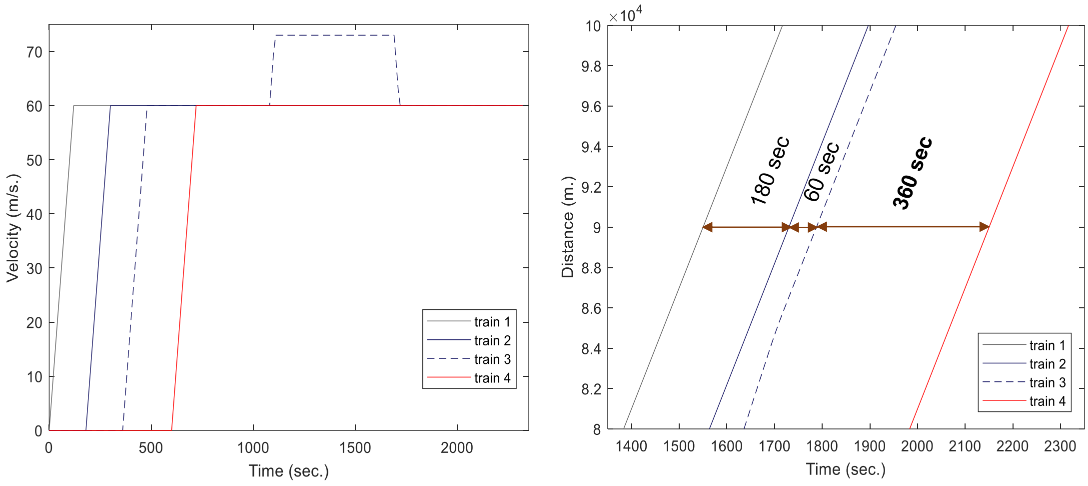
Therefore, the trains 1, 2, 3, and 4 will be built into the same convoy by adjusting their velocity to 60 m/s, 67 m/s, 74 m/s, and 80 m/s respectively when the second train reaches the merging point.

Example 3-12: Building the leading convoy

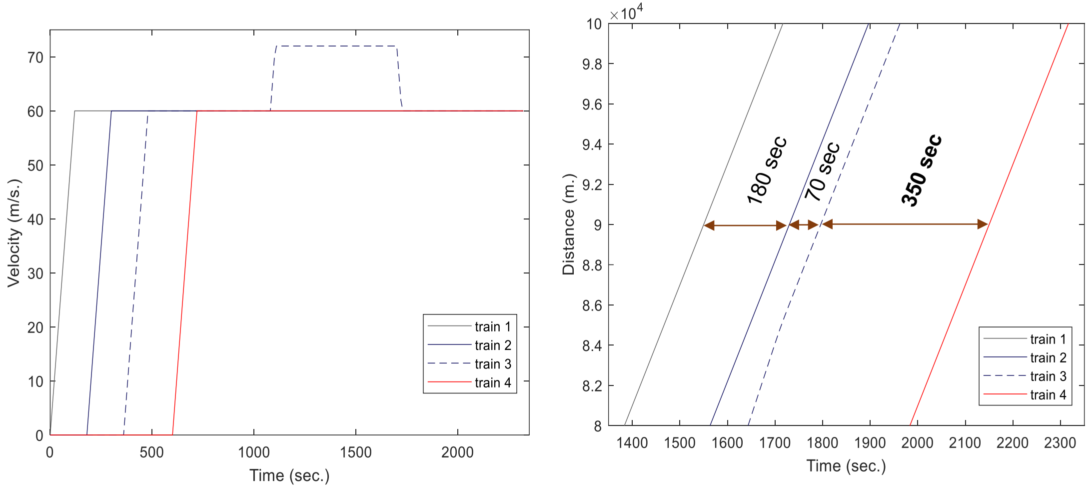
Four trains will operate along the route A (70 m/s velocity limit). They will operate with the same velocity of 60 m/s approaching the converging junction. Based on their ideal velocity profile, the estimated headway time between the train 3 and the inserted train m is about 60 sec. It is lower than minimum safe headway at 180 sec. In this case, 120 sec extra time gap (or 7200 m extra separation distance) behind the train 3 must be extended. In the other words, the time gap between train 3 and train 4 should be at least 360 sec for inserting the inserted train m into the same route safely. By checking the estimated reaching time, the time gap behind the train 3 could be lengthened by merging the train 2 and train 3 into the leading convoy. So, the train 3 will accelerate to its optimal merging velocity when reaching the merging point set at 50 km away from the junction (42.7 km measured from the beginning of safe zone). Thus, the optimal merging velocity for the train 3 is

$$\mathrm{v}_3^{\mathrm{mer}} = \mathrm{v}_2^{\mathrm{mer}} \Big/ \left(1 - \frac{\Delta \mathrm{x}_{\mathrm{Lead}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right) = \frac{60}{\left(1 - \left(\frac{7200}{42700}\right)\right)} = 73\ \mathrm{m/s}$$

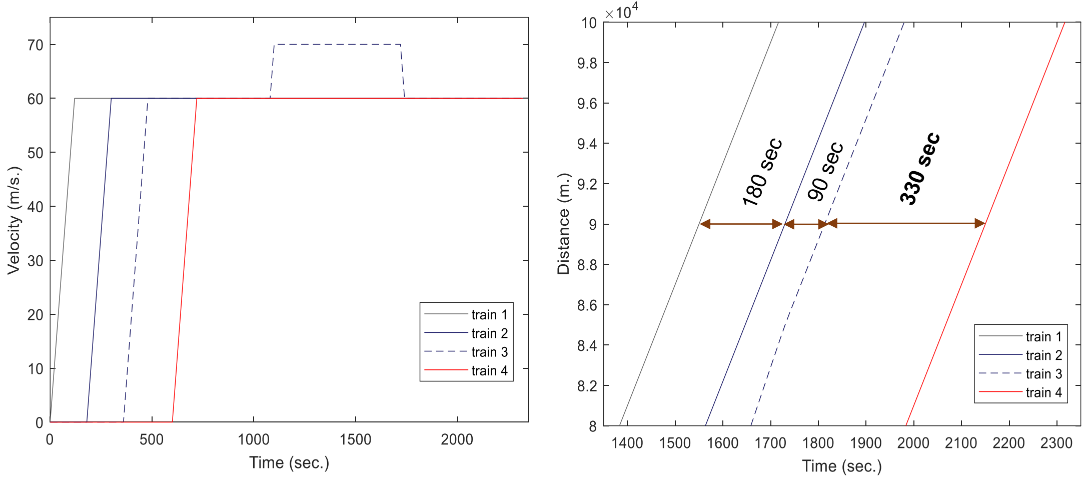
Figure 3.25 (A) shows the velocity-time and distance-time profile of trains in the leading convoy. It is seen that the time gap between train 2 and train 3 is reduced from 180 sec to 60 sec while the time gap between the train 3 and 4 measured when passing the junction is increased from 240 sec to 360 sec. It is high enough allowing the train m to be inserted into the same route safely. However, the velocity limit along the route is only 70 m/s. Building the train convoy by using a lower merging velocity lower than 73 m/s could not increase the time gap behind the convoy to 360 sec. If the train 3 accelerates to 72 m/s for merged into the convoy **Figure 3.25 (B)**, the time gap between train 3 and 4 is increased from 240 sec to 350 sec which is not high enough for inserting the extra train m. However, due to the maximum velocity limit restricted at 70 m/s, the train 3 could accelerate to only 70 m/s. It is found that the the headway time between train 3 and train 4 has been extended from 240 sec to 330 sec lower than the minimum time gap required for inserting the train m (**Figure 3.25 (C)**).



(A) v_2^{mer} = 60 m/s and v_3^{mer} = 73 m/s



(B) v_2^{mer} = 60 m/s and v_3^{mer} = 72 m/s



(C) v_2^{mer} = 60 m/s and v_3^{mer} = 70 m/s

Figure 3.25 Extended time gap behind the leading convoy

2) Optimal merging velocity for a train in a following convoy

Similar to the process for building a leading convoy, the optimal merging velocity of trains in a following convoy can be calculated relaying on the extra time gap required for inserting an extra train ($\Delta t_{\mathrm{Follow}}^{\mathrm{ext}}$). According to the merging pattern for building a following convoy described in **Section 3.4.2.5**, the front trains in a convoy will decelerate and operate by a lower velocity than their front train to lengthen the gap in front of a convoy. It is recommended that the last train in a following convoy (the reference train) should proceed by its optimal velocity through the merging state for preventing delay time impacting on the trains running behind.

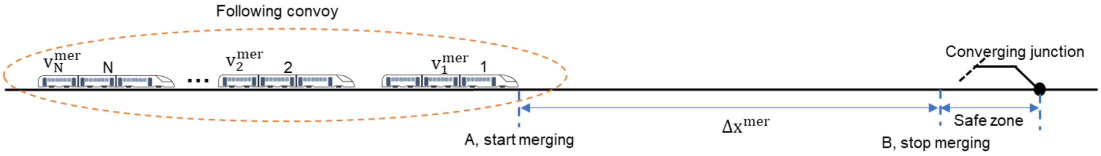


Figure 3.26 Building a following convoy

The extended separation distance in front of a following convoy ($\Delta x_{\mathrm{Follow}}^{\mathrm{ext}}$) could be estimated by **Equation (3-55)**.

$$\Delta x_{\mathrm{Follow}}^{\mathrm{ext}} = v^{\mathrm{maxp}} \times \Delta t_{\mathrm{Follow}}^{\mathrm{ext}} \tag{3-55}$$

The merging pattern for building a following convoy is shown in **Figure 3.26**. The trains will start merged into a convoy when the first train a convoy reaches the merging point (x^{mer}). They will decelerate to their optimal merging velocity at the same time. The total time that the first and the last train in a convoy have proceeded for lengthening the distance in front of the convoy for $\Delta x_{\mathrm{Follow}}^{\mathrm{ext}}$ is

$$\Delta t_1^{\mathrm{mer}} = \frac{\Delta x_{\mathrm{Follow}}^{\mathrm{ext}}}{(v_N^{\mathrm{mer}} - v_1^{\mathrm{mer}})} \tag{3-56}$$

The total time that the first train has operated through the merging distance is $\Delta t_1^{\mathrm{mer}} = \Delta x^{\mathrm{mer}}/v_1^{\mathrm{mer}}$. This term is placed into **Equation (3-56)** for estimating the optimal merging velocity of the first train (v_1^{mer}). Thus, the v_1^{mer} can be calculated by **Equation (3-57)**.

$$v_1^{\mathrm{mer}} = v_N^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta x_{\mathrm{Follow}}^{\mathrm{ext}}}{\Delta x^{\mathrm{mer}}}\right)\right) \tag{3-57}$$

In the case that there are more than two trains will be built into the same convoy, the optimal merging velocity of the middle trains can be calculated by using **Equation (3-50)**.

Example 3-13: Building the following convoy: two trains built into the same convoy

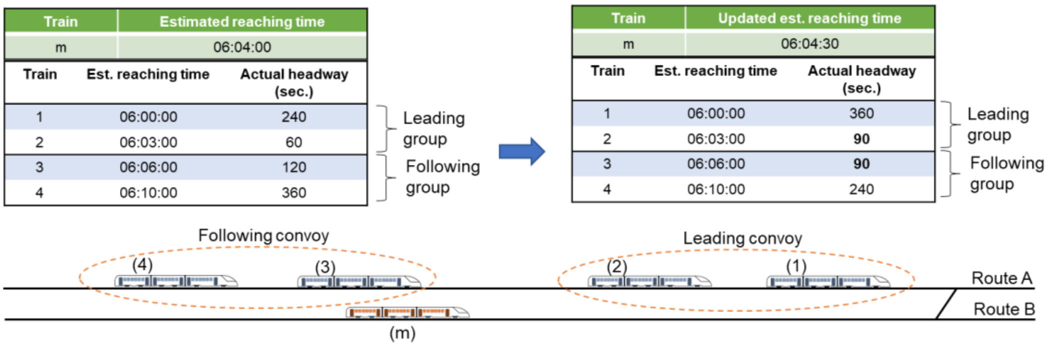
Referring to the example shown in **Figure 3.21**, four trains will operate along the main route. Based on the existing timetable, the estimated reaching time of the trains is shown in **Figure 3.27**. The extra train from another route will be inserted to operate along the same route. It will reach the converging junction at 06:04:00. The estimated reaching time of all trains is compared to the inserted train's estimated reaching time for determining whether the trains should be built together as a train convoy.

By comparing their estimated reaching times, the train 1 and 2 will be merged as a leading convoy while the train 3 and 4 will be built into the following convoy. It is seen that the headway time between the train 2 and the inserted train m is only 60 sec less than minimum headway time at 180 sec. Thus, 120 sec extended time gap between the train 2 and train 3 is required.

In this case, the train 2 should accelerate to 73 m/s for merged into the same convoy with the train 1 to lengthen the time gap behind the convoy. However, the train 2 can accelerate to 70 m/s at maximum due to the velocity limit allowed for passing the junction. As a result, the time gap extended after building the leading convoy is lower than the required extended time gap. By estimating the extended time gap behind a leading convoy, approximately 90 sec could be extended. Thus, 30 sec will be added to update the estimated reaching time gap of the inserted train m.

Example 3-13: (cont.)

In this case, the inserted train m should slow down for keeping safe headway away from the train 2. The estimated reaching time of the train m will be changed from 06:04:00 to 06:04:30. After updating the estimated reaching time of the train m, the estimated headway times between the inserted train m and the trains in the following convoy are updated as shown in the right box in **Figure 3.27**. It is seen that the headway time between the inserted train m and the first train in the following convoy (train 3) is decreased from 120 sec to 90 sec. Thus, to insert the train m into the same route safely, 90 sec extra time gap or 5.4 km extra separation distance is required after building the following convoy.



Train	Estimated reaching time
m	06:04:00

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	240
2	06:03:00	60
3	06:06:00	120
4	06:10:00	360

Train	Updated est. reaching time
m	06:04:30

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	360
2	06:03:00	**90**
3	06:06:00	**90**
4	06:10:00	240

Figure 3.27 Updated estimated headway time

The optimal merging velocity of the train 3 is

$$v_3^{mer} = v_4^{mer} \Big/ \left(1+\left(\frac{\Delta x^{ext}_{Follow}}{\Delta x^{mer}}\right)\right) = 60 \Big/ \left(1+\left(\frac{5400}{44000}\right)\right) = 53\ m/s$$

Thus, the train 3 and train 4 should proceed by 53 m/s and 60 m/s respectively through the merging distance for merged as the following convoy. **Figure 3.28** shows the simulated velocity-time and distance-time profile of this example. It is obviously seen that the separation distance between train 2 and train 3 has been lengthened.

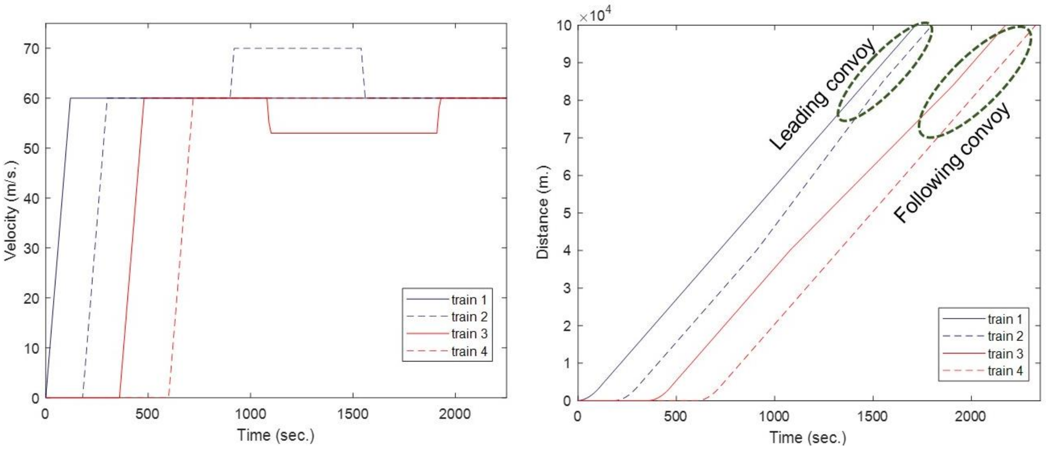
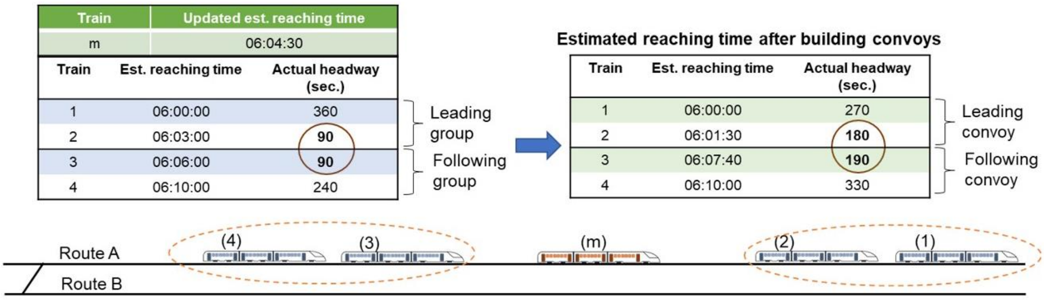


Figure 3.28 Building 2 trains into the following convoy

Example 3-13: (cont.)

The updated estimated reaching time of the train 1, train 2, train 3, and train 4 after built into the convoys is shown in **Figure 3.29**. It is seen that the time gap between train 2 and train 3 has been increased from 180 sec to 370 sec that is higher than the minimum time gap required for inserting the train m.



Train	Updated est. reaching time
m	06:04:30

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	360
2	06:03:00	**90**
3	06:06:00	**90**
4	06:10:00	240

Estimated reaching time after building convoys

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	270
2	06:01:30	**180**
3	06:07:40	**190**
4	06:10:00	330

Figure 3.29 Updated estimated reaching time after building the convoys

Thus, it could be confirmed that the train m could be inserted into the route A safely in that the headway time away from its leading train 2 and following train 3 is not lower than the minimum headway time required for passing the junction.

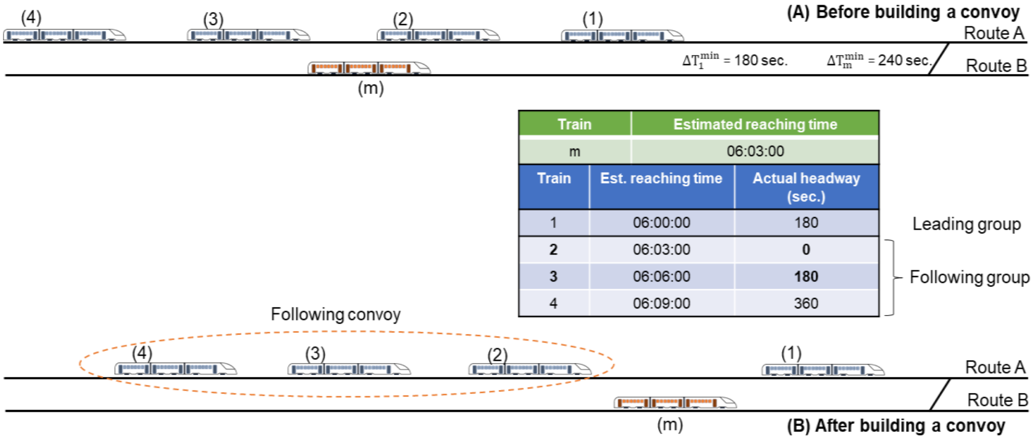
Example 3-14: Building the following convoy: three trains built into the same convoy

Within 9 min defined time period, four trains will operate on the route A by the same velocity keeping 3 min headway time. The train m proceeding on the route B will insert into the route A and will reach the junction by estimated time shown in **Figure 3.30**. Assuming that the maximum velocity restricted for passing the junction is 60 m/s while the velocity limit along the route is 70 m/s.

By comparing the estimated reaching time, only the train 1 is classified to be built as a leading convoy. The headway time away from the inserted train m is 180 sec equalling to the minimum headway time required for passing the junction. In this case, the inserted train m could reach the junction by its estimated reaching time at 06:03:00. It will reach the junction by the same time as the train 2 (the first train in the following convoy). It means that there is no time gap between train m and train 2 when passing the junction. Assuming that the minimum headway time between train 2 and train m is 240 sec. So, at least 240 sec extra time gap (or 14.4 km separation distance) is required in front of the following convoy.

Example 3-14: (cont.)

As the headway time from train m to both train 2 and 3 is less than the minimum headway time, both train 2 and 3 should be merged into the same convoy with the reference train 4 for increasing the time gap in front of the convoy.



Train	Estimated reaching time
m	06:03:00

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	180
2	06:03:00	**0**
3	06:06:00	**180**
4	06:09:00	360

Figure 3.30 Building three trains into the same convoy

It is suggested that the last train 4 should proceed by constant velocity at 60 m/s through the merging state. Assuming that the merging point is set at 50 km away from the junction. So, both train 2 and train 3 will adjust their velocity when the train 2 (the first train in the following convoy) reaches the merging point at 44 km away from beginning of safe zone. The optimal merging velocity of the train 2 is

$$v_2^{mer} = v_4^{mer} \Big/ \left(1 + \left(\frac{\Delta x_{Follow}^{ext}}{\Delta x^{mer}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{14400}{44000}\right)\right) = 45 \text{ m/s}$$

And the optimal merging velocity gap (Δv^{omer}) between successive trains is

$$\Delta v^{omer} = \frac{(v_N^{mer} - v_1^{mer})}{K} = \frac{(60 - 45)}{2} = 8 \text{ m/s}$$

The optimal velocity that the train 2, train 3, and train 4 should operate through the merging state is 45 m/s, 52 m/s, and 60 m/s respectively. **Figure 3.31** shows the simulated velocity-time and distance-time profile when building three trains into the same convoy. It is seen that the headway time between train 2 and train 3, and the train 3 and train 4 is decreased extending the time gap in front of the train 2.

Example 3-14: (cont.)

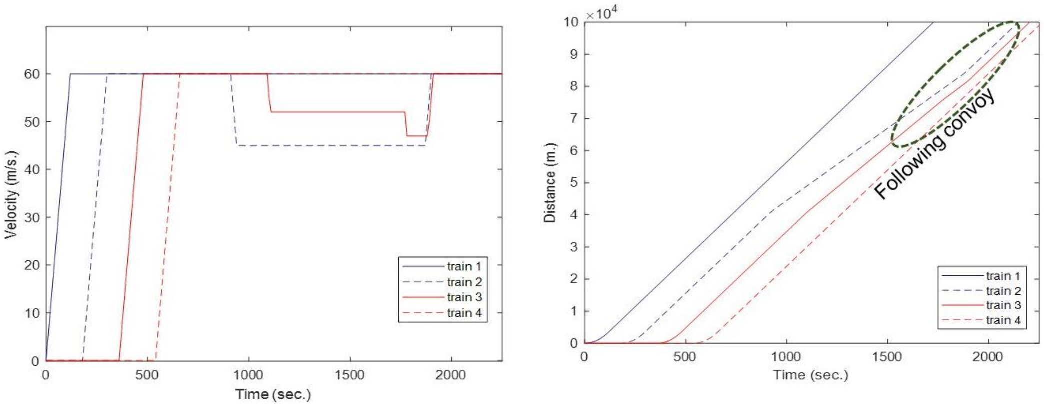
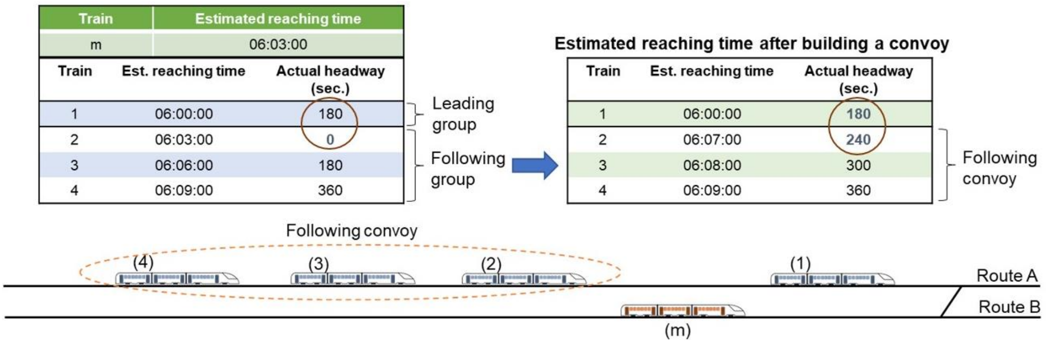


Figure 3.31 Simulated velocity and distance profiles: three trains built into the same convoy

The estimated reaching time of trains when passing junction before and after building the following convoy is shown in **Figure 3.32**. It is seen that the headway time in front of the train 2 after building the following convoy is increased by 240 sec that is high enough for inserting the train m into the main route.



Train	Estimated reaching time
m	06:03:00

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	180
2	06:03:00	0
3	06:06:00	180
4	06:09:00	360

Estimated reaching time after building a convoy

Train	Est. reaching time	Actual headway (sec.)
1	06:00:00	180
2	06:07:00	240
3	06:08:00	300
4	06:09:00	360

Figure 3.32 Updated estimated reaching time: three trains built into the following convoy

To sum up, the route capacity in terms of the number of trains within the defined time period could be increased by merging trains as a train convoy for passing through the converging junction. The time gap in front of and/or behind the convoy is increased allowing any trains from other routes to be inserted. A convoy will be built by different merging patterns depending on the estimated reaching time compared to the reaching time of an inserted train. The equations used to calculate the optimal merging velocity of trains in both leading and following convoys are summarized in **Table 3.3**.

Table 3.3 Optimal merging velocity equations

Train	Convoy types	
	Leading convoy	**Following convoy**
First train	$v_1^{mer} = v^{opt}$	$v_1^{mer} = v_N^{mer} \Big/ \left(1 + \left(\frac{\Delta x_{Follow}^{ext}}{\Delta x^{mer}}\right)\right)$
Last train	$v_N^{mer} = \min\left[v^{max}, \left(v_1^{mer} \Big/ \left(1 - \frac{\Delta x_{Lead}^{ext}}{\Delta x^{mer}}\right)\right)\right]$	$v_N^{mer} = v^{opt}$
Middle(s)	$v_{k+1}^{mer} = \max[(v_k^{mer} + \Delta v^{omer}), v_N^{mer}]$	

3.5 VCS applications used in operating state

As the convoy proposal could be sent from a leading or a following train, the communication flow topology named “bidirectional leader type” (**Figure 3.33**) is used. A train could send and receive the data from its adjacent trains that could be either a train in front or a train running behind. In addition, the first train in each convoy can send the information to all involved trains proceeding behind (S. E. Li et al., 2017).

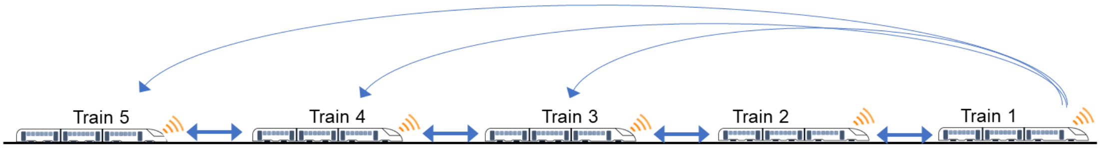


Figure 3.33 Communication flow topology

In operating state, four VCS applications (**Table 3.4**) will be used in different situations. **Figure 3.34** shows the flowchart to determine which VCS application should be applied. A train’s velocity is continuously checked and then compares with its ideal velocity. If a train operates by using a lower velocity $v_k(t) < v_k^{idl}(t)$, delay may occur. Then, a train position is checked. If a train decelerates, a following will be forced to decelerate causing delay as well if the distance between trains is shorter than minimum safe distance under the MBS. To reduce delay of a following train, the **VCS Application 1** is applied to merge a delayed train and an impacted train into the same convoy. When a train convoy approaches a junction, some trains may be forced to operate by a lower velocity to lengthen the distance separated from a train ahead. The distance between some couples of trains may be shorter than minimum safe distance at a junction forcing a following train to decelerate causing secondary delay. In this case, the **VCS Application 2** is applied to reduce delay by merging a delayed trains and an impact train as a train convoy for passing a junction.

Table 3.4 VCS applications used in operating state

Applications	Situations
Application 0	A train operates under the MBS.
Application 1	Applying the VCS to reduce delay time when a train delay impacts any trains running behind.
Application 2	Applying the VCS to reduce delay time when a train convoy approaches a junction.
Application 3	Building trains into a train convoy for increasing capacity. The involved trains will be merged into a train convoy according to the planned timetable.
Application 4	Building trains into a train convoy for increasing capacity. The optimal merging velocity and involved trains are changed due to delay before start building a convoy.

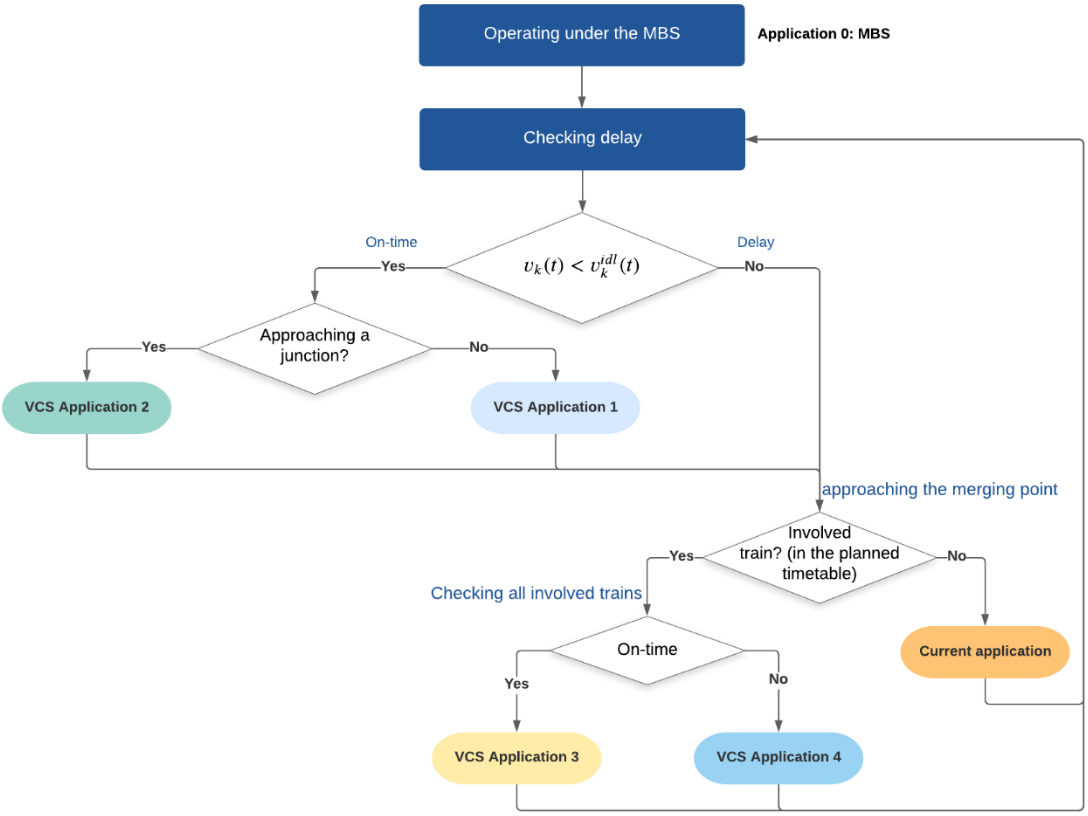


Figure 3.34 The flowchart determining to apply the VCS applications

Note: the ideal velocity ($v_k^{idl}(t)$,) refers to the optimal velocity, or the velocity that a train can proceed based on the original timetable.

When the involved trains (as stated in the planned timetable) approach the merging point, the **VCS Application 3** will be applied if all involved trains in the same convoy operate on-time. If not, the VCS Application 4 is used for redetermining a set of involved trains and recalculating the optimal merging velocity. The flowchart and the conditions needed to be considered before sending and after receiving the convoy proposal in each application are explained below.

3.5.1 **VCS application 1:** Building a train convoy to reduce delay

This application will be used when a train delays. It may force its following train to decelerate causing delay as well of the distance between trains is shorter than minimum safe distance under the MBS. To reduce delay, the idea is to merge a delayed train and its following train (an impacted train) as a train convoy to allow an impacted train still proceeding by optimal velocity.

Figure 3.35 shows the train movement of this situation. When the distance between trains is shorter than minimum safe distance under the MBS, a following train is normally forced to decelerate for maintaining safe distance separated from its front train. Using the VCS to couple both trains together as a train convoy could reduce secondary delay. A following train is not forced to decelerate and could still operate by the ideal velocity if the distance away from a delayed train is still longer than minimum safe distance under the VCS.

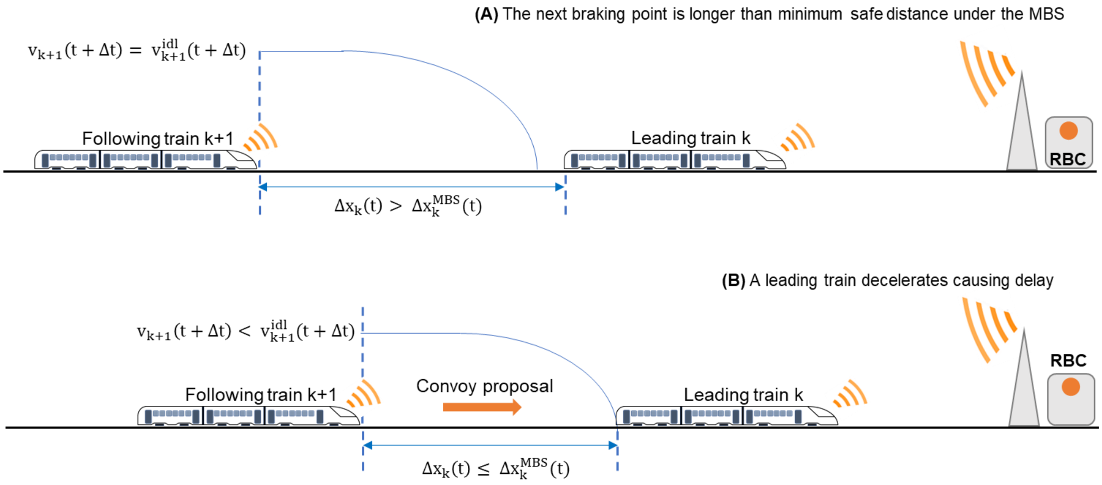


Figure 3.35 Sending the convoy proposal when $v_{k+1}(t+\Delta t) < v^{idl}_{k+1}(t+\Delta t)$

Figure 3.36 illustrates the flowchart showing what is the conditions determined before building convoy in case of delay. Basically, a train knows its ideal velocity that it will operate along each route section. When a train delays, the distance from its following train is decreased. The following train will send the convoy proposal to the leading train (the delayed train) if it cannot operate by its ideal velocity.

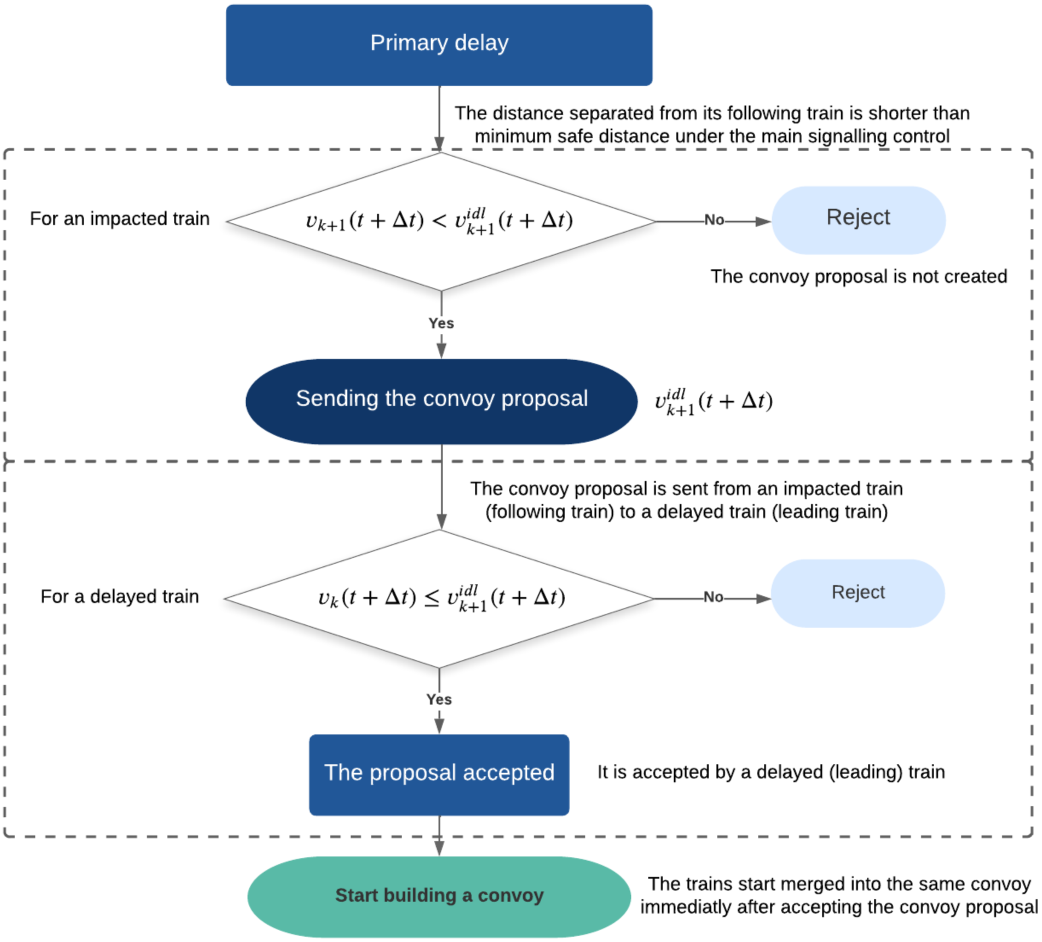


Figure 3.36 The flowchart of the VCS Application 1

The optimal operating velocity of the following train in the next time step ($v_{k+1}(t+\Delta t)$) is calculated by a train itself using the movement authority obtained from the control centre. If a train delays but the distance away from its following train is still longer than minimum safe distance under the MBS, the convoy proposal is not created because the following can still operate by its ideal velocity. If a train could operate by velocity lowering than its ideal velocity, the convoy proposal including the ideal velocity in the next time step $v_{k+1}^{idl}(t+\Delta t)$ will be sent to its leading train requesting to be merged as a train convoy (**Equation (3-58)**).

$$v_{k+1}(t+\Delta t) < v_{k+1}^{idl}(t+\Delta t) \tag{3-58}$$

Example 3-16: Will the convoy proposal be created?

Two trains operate with the same ideal velocity at 60 m/s maintaining 12 km separation distance between them. Assuming that minimum permissible headway time under the MBS is 3 min (10.8 km). Thus, the convoy proposal will be created when the distance between train is less than 10.8 km. This is because when the distance between them is shorter than 10.8 km, the velocity limit of the following train in the next time step will be lower than its ideal velocity at 60 m/s.

Then, the ideal velocity of the impacted train ($\mathrm{v}_{\mathrm{k}+1}^{\mathrm{idl}}(\mathrm{t}+\Delta\mathrm{t})$) will be compared to the optimal velocity of its leading train ($\mathrm{v}_{\mathrm{k}}(\mathrm{t}+\Delta\mathrm{t})$) to determine the trend of separation distance between trains. The delayed train will accept the convoy proposal if its operating velocity in the next time step ($\mathrm{v}_{\mathrm{k}}(\mathrm{t}+\Delta\mathrm{t})$) is equal to or lower than the ideal velocity of the impacted train operating behind ($\mathrm{v}_{\mathrm{k}+1}^{\mathrm{idl}}(\mathrm{t}+\Delta\mathrm{t})$).

$$\mathrm{v}_{\mathrm{k}}(\mathrm{t}+\Delta\mathrm{t}) \leq \mathrm{v}_{\mathrm{k}+1}^{\mathrm{idl}}(\mathrm{t}+\Delta\mathrm{t}) \tag{3-59}$$

Example 3-15: Will the convoy proposal be accepted?

Two trains operate under the MBS using the same ideal velocity at 60 m/s keeping 3 min headway time between them. The headway time between them is equal to the minimum permissible headway time under the MBS. Assuming that the leading train decelerates to 58 m/s for only 10 sec and then accelerates to 62 m/s to recover its timetable. The velocity of the leading train in the next time step is 62 m/s while the following train’s velocity is 60 m/s. As a result, the distance between trains has been extended due to a higher velocity of the leading train. In this case, the convoy proposal is rejected.

If the leading train has operated by 58 m/s for longer, the leading train’s velocity in the next time step is lower than the operating velocity of its following train. In this case, the convoy proposal will be accepted. Then, both trains will start merged as a train convoy immediately after accepting the convoy proposal.

If the impacted train (the following train) operate by a higher velocity than the delayed train, the convoy proposal will be accepted. Otherwise, the convoy proposal will be rejected. The involved trains will start merged into the same convoy immediately after accepting the convoy proposal. Then, they will operate based on the proposed approach shown in **Section 3.2**.

3.5.2 **VCS application 2:** Building a new train convoy when approaching a diverging junction

When trains have been built as a train convoy, the distance between successive trains is basically shorter than minimum safe distance required at a junction. If successive trains in a train convoy continue on different routes after passing through a junction, a following train is normally stimulated to operate by a lower velocity than its front train for lengthening the separation distance between them. Due to the deceleration of a following train, a train proceeding behind it will be forced to decelerate causing delay as well although they will continue on the same route after passing a junction.

To reduce the secondary delay when a train convoy has passed through a junction, the idea is to build a delayed train and any impacted trains running behind that will continue on the same route as a train convoy. An impacted train may not be forced to decelerate and can proceed by its ideal velocity without delay. **Figure 3.37** shows the flowchart of the VCS Application 2. It could be applied to reduce secondary delay when a train convoy has passed through a junction. Similar to the flowchart of the VCS application 1, a train's velocity has been checked and compared to its ideal velocity. If the velocity of the impacted train in the next time step ($\mathrm{v_{k+1}(t+\Delta t)}$) is lower than the ideal velocity ($\mathrm{v_{k+1}^{idl}(t+\Delta t)}$), the convoy proposal including the ideal velocity ($\mathrm{v_{k+1}^{idl}(t+\Delta t)}$) and route detail ($\mathrm{R_{k+1}}$) of an impacted train will be sent to a delayed train in front.

Two conditions are considered before accepting the convoy proposal. A delayed train will accept the convoy proposal if its velocity in the next time step is equal to or lower than the ideal velocity of the impacted train (**Equation (3-59)**) and if it continue on the same route with the impacted train (**Equation (3-60)**).

$$\mathrm{R_k = R_{k+1}} \tag{3-60}$$

After accepting the convoy proposal, the delayed train and the impacted train will start merged into the same convoy by following the proposed state movement in the **Section 3.2**. It is noted that the splitting velocity of the delayed train is also the merging velocity that it has been merged as a train convoy with the impacted train.

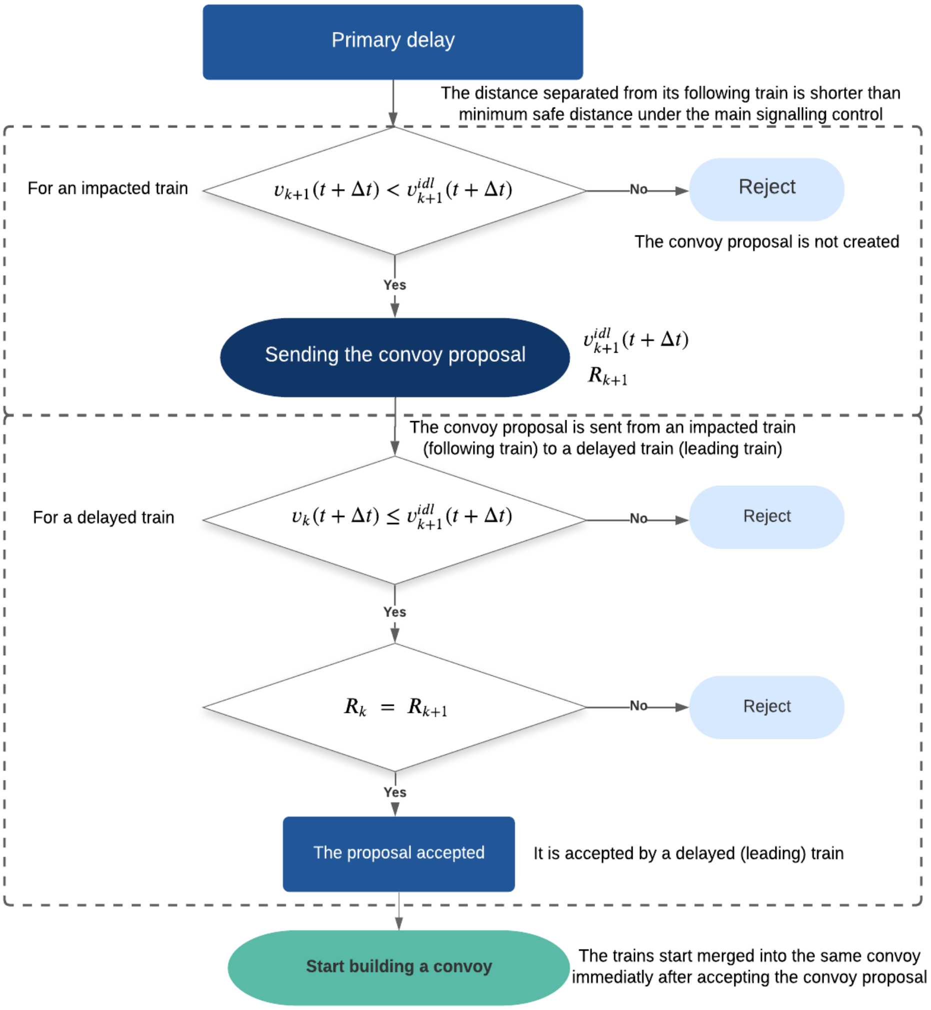


Figure 3.37 The flowchart of the VCS Application 2

Figure 3.38 shows the example of movement of the trains after applying the VCS application 2. The train 1 and train 2 coupled into the same convoy is approaching the junction. Then, they will continue on different routes after passing the junction. The train 2 needs to operate by a lower velocity than the train 1 because the current distance separated from the train 1 is shorter than minimum safe distance required for passing the junction safely. As the decrease of operating velocity of the train 2, the distance separated from the train 3 is decreased reducing maximum velocity of the train 3 in the next time step. Assuming that the train 2 and train 3 continues on the same route after passing the junction, they could be merged into the same convoy for reducing secondary delay in the train 3. By applying the VCS Application 2, the impacted train 3 will not be forced to decelerate instantly although the distance from the train delayed 2 is shorter than the minimum safe distance under the MBS. It could operate by ideal velocity for merged as a train convoy with the delayed train 2.

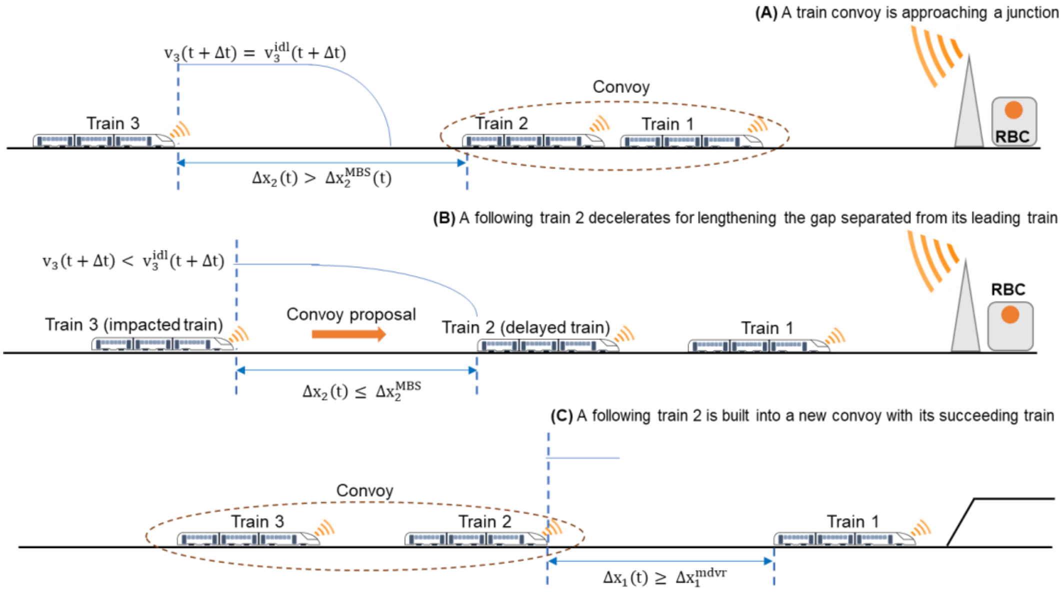


Figure 3.38 Building a train convoy when approaching a diverging junction

If the delayed train 2 and the impacted train 3 continue on the different routes (**Figure 3.39**), the train 3 will be forced to slow down causing delay as well when the distance away from the delayed train 2 is shorter than minimum safe distance at the junction. It will impact the movement of a train running behind (the impacted train 4). In this case, the impacted train 4 will send the convoy proposal requesting to be merged into the same convoy with the delayed train 3.

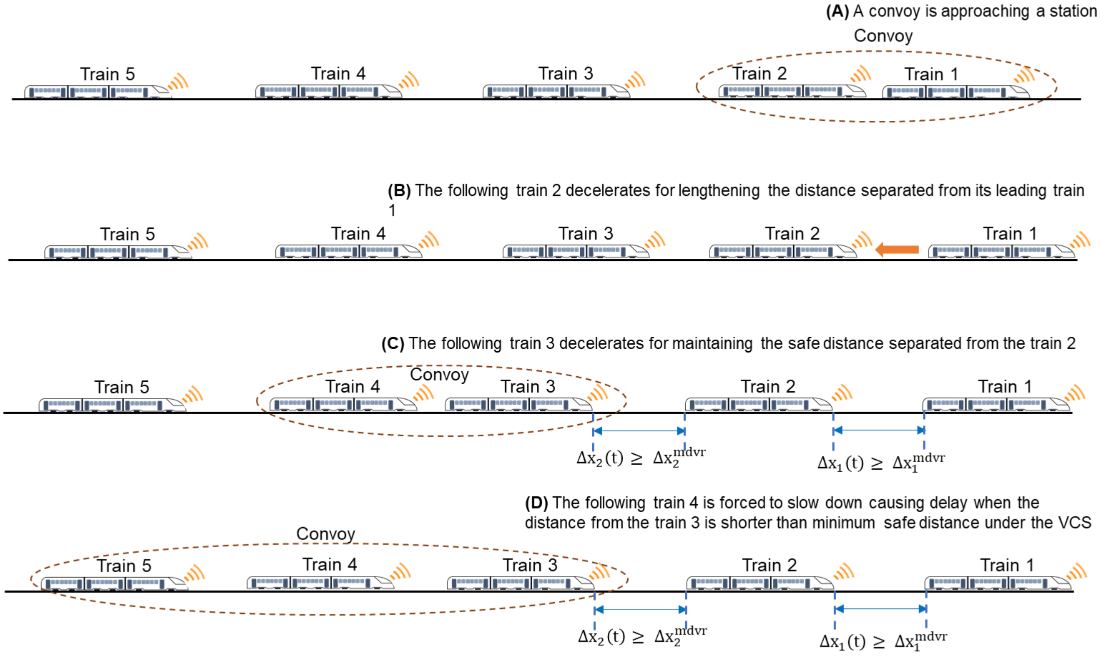


Figure 3.39 Reducing delay by applying the VCS application 2

3.5.3 **VCS application 3:** Building a train convoy according to the planned timetable

In the planned timetable (**Section 3.4**), we know which trains will be built into a train convoy, the involved trains in each convoy, and the optimal merging velocity that each train will proceed for merged into a train convoy. The VCS Application 3 will be used for building a train convoy according to the planned timetable. It is used in the case that trains within the defined time period have operated on-time and have not been built in another convoy before reaching the merging point.

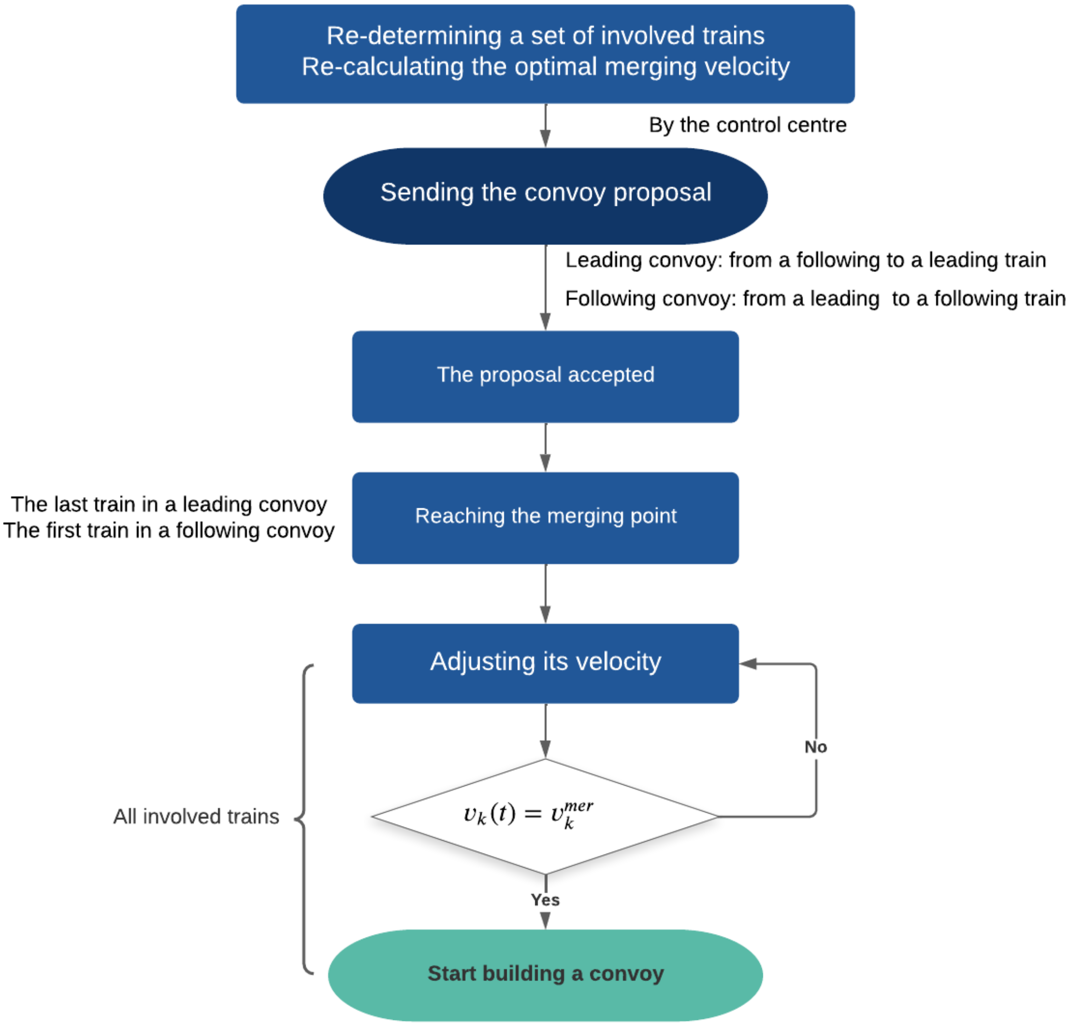


Figure 3.40 The flowchart of the VCS Application 3

If a train could operate on-time and not be built into any convoy before reaching the merging point, it will be merged into a train convoy with its involved trains and by using the optimal merging velocity suggested in the planned timetable. A train's travelling distance has been measured comparing to the ideal distance that it should be at the specific time to check whether it delays. It has operated on-time if its travelling distance at a time (t) is longer than the ideal distance (**Equation (3-61)**).

$$x_k(t) \geq x_k^{idl}(t) \tag{3-61}$$

Also, the convoy status is also checked whether it is built in another convoy before reaching the merging point. When a group of involved trains is approaching the merging point, the first train will send the convoy proposal to all involved trains to inform the following trains to prepare to be merged into the same convoy. It is noted that all involved trains start merged into a train convoy at the same time. When the last train in leading convoy or the first train in a following convoy reaches the merging point, all involved trains will start to adjust its velocity according to the optimal merging velocity stated in the planned timetable.

3.5.4 **VCS application 4:** Redetermining a train convoy

The VCS Application 4 is applied for the same reason as the VCS Application 3. But this application will be applied when any involved trains could not operate according to the planned timetable. In this case, the estimate reaching time of a train is changed, in which the involved train and optimal merging velocity must be recalculated again by the control centre. As the trains have reported the current information (current position, velocity, convoy status, and route) to the control centre, the control centre will use their current information to re-determine the involved trains in each convoy, and to re-calculate the optimal merging velocity sending back to the involved trains (**Figure 3.40**).

When the involved trains are approaching the merging point, their position ($x_k(t)$) is measured and compared to the ideal position that they should be at the same time ($x_k^{idl}(t)$). In the case that any trains are delayed (**Equation (3-62)**) or already built in another convoy, the VCS application 4 is applied.

$$x_k(t) < x_k^{idl}(t) \tag{3-62}$$

After obtaining the updated involved trains and optimal merging velocity from the control centre. The first train will send the convoy proposal to all involved trains proceeding behind. Then, they will start adjusting their velocity when the last train in a leading convoy or the first train in a following convoy reaches the merging point.

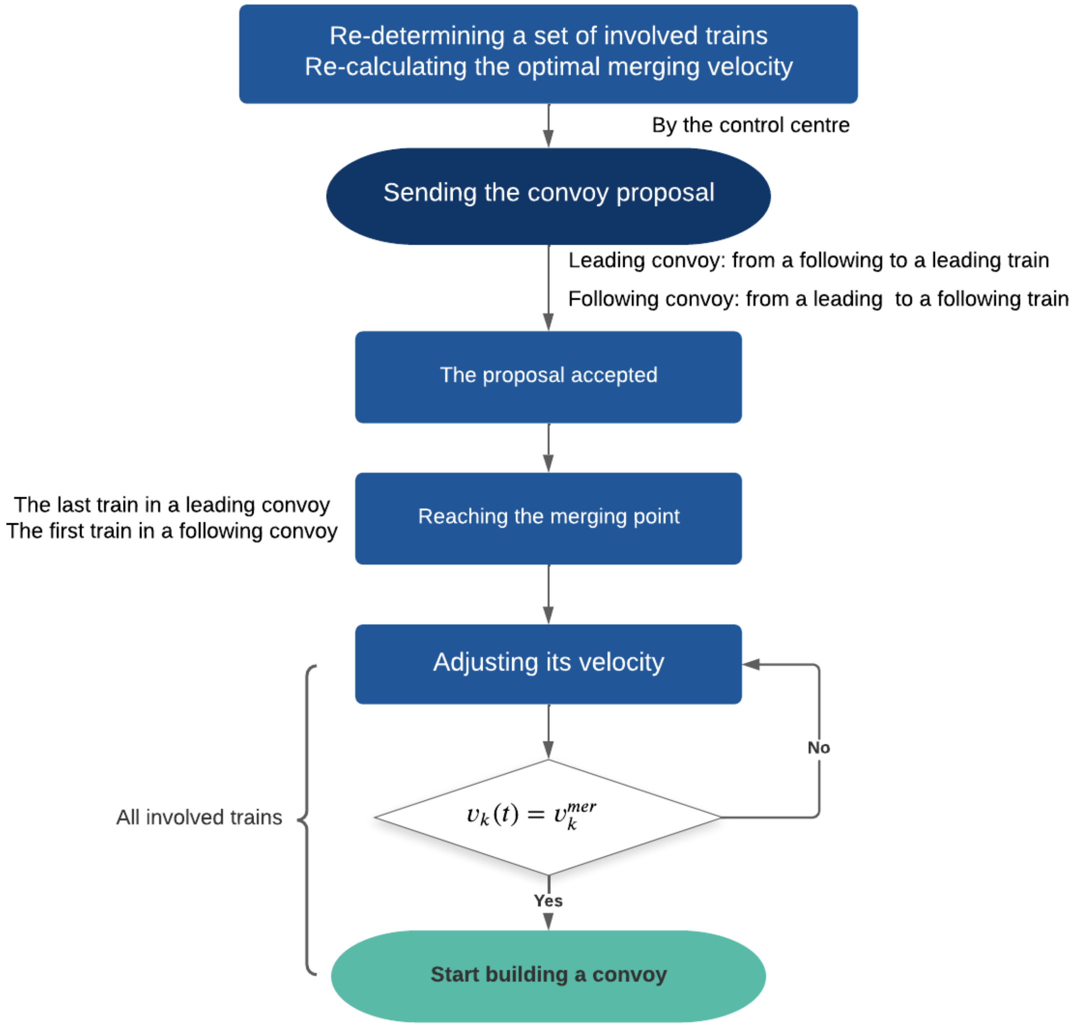


Figure 3.41 The flowchart of the VCS Application 4

Chapter 4

Controlling trains operating under the virtual coupling system

4.1 Introduction

Referring to the previous studies shown in **Chapter 2**, it could be definitely concluded that the route capacity could be increased by building a group of trains as a train convoy (Flammini et al., 2019). Trains in a convoy operate based on the Virtual Coupling System (VCS) by maintaining safe distance separated from a train ahead. This will help route capacity to be increased, in which more trains could operate along the same route compared to the maximum number of trains operating under the MBS.

Currently, many approaches such as the approaches introduced by Henke, Ticht, Schneider, Bocker, & Schafer (2008); Henke & Trachtler (2013) have been proposed for simulating a following train movement under the VCS. These approaches could be effectively used for simulating train movement but there are some shortcomings such as exceeding gap between trains, unsafe movement, unstable travelling, and unrealistic acceleration and deceleration rate.

4.2 Objectives

In this chapter, the aim is to determine the effectiveness of the proposed approach for controlling a following train's movement under the VCS. The approach should achieve three objectives explained below.

4.2.1 Increasing route capacity

The first objective is to increase route capacity by controlling the separation distance between successive trains. The number of trains within defined time period must be higher than the number of trains under the MBS. The theoretical maximum number of trains when proceeding along plain route, passing a converging junction, and passing a diverging junction are calculated by **Equation (3-26)**, **Equation (3-27)**, and **Equation (3-28)** respectively.

4.2.2 Improving safety

It is noted that trains could operate safely if the separation distance between any successive trains is longer than the minimum safe distance. To determine the effectiveness of the proposed approach in safety aspect, the simulated distance between trains has been measured and compared with the minimum safe distance. **Equation (3-29)** is used to determine the safety aspect when a train convoy has operated along plain route and when it has passed a converging junction. When a train convoy has passed a diverging junction, **Equation (3-30)** is used.

4.2.3 Improving movement stability

The proposed approach can be used well to simulate trains operating under the VCS if a following train can obtain stable travelling. It is effective if a following train can proceed by using constant velocity for merged into the same convoy with its front train although the distance between trains is still longer than the minimum safe distance. It can split out from a train convoy using constant velocity and can complete splitting state when the distance separated from a leading train is longer than minimum safe distance under the MBS. Also in convoy state, a following train can proceed in relation to the movement of a leading train. It will accelerate when a leading train accelerates, decelerates when if a leading train applies brake, and proceed by constant velocity if a leading train has moved by constant velocity. **Equation (3-33)** is used to the determine the movement stability of a following train under the VCS.

4.2.4 Splitting from a train convoy more effectively

When a train convoy approaches a diverging junction, the distance between trains must be lengthened until it is longer than minimum safe distance at a junction. **Equation (3-30)** is used to evaluate whether a following train split out from a train convoy and pass a junction safely. It would pass a junction safely if the distance separated from a leading train is longer than minimum safe distance required for passing a junction.

4.3 Methodology

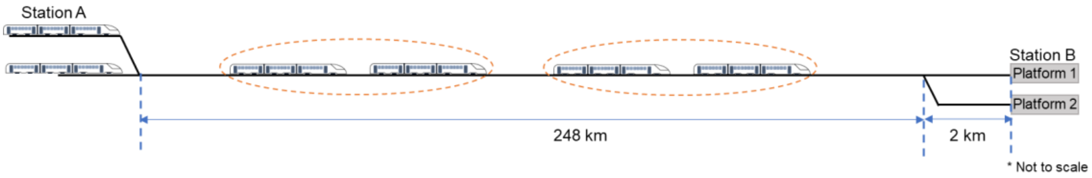
A following train's movement is simulated using the **MATLAB (R2019b)** programming. The coding is built based on the state movement's conditions in **Section 3.2**. The possible causes of shortcomings in previous approaches and the solutions that will be used to improve the proposed approach are summarized in **Table 4.1**.

Table 4.1 The methodology to improve the VCS approach

Shortcomings	Possible causes	Methodology
1) Low capacity	1) Unrealistic or high braking rate. 2) Fixed minimum safe distance.	1) Proposing equations to calculate optimal braking rate (**Equation (3-14)**) 2) Introducing the equation to calculate real-time minimum safe distance (**Equation (3-10)**) and proposing the state movement to control the distance between trains when they are in convoy state (**Section 3.2.1**)
2) Unsafe movement	1) Minimum safe distance equation. 2) Fixed or unrealistic acceleration/deceleration rate. 3) Conditions for transferring to the convoy state.	1) Modifying the minimum safe distance equation (**Equation (3-10) in the Section 3.1**) 2) Proposing equation to calculate optimal accelerate/deceleration rate (**Equation (3-13)** and **(3-14)**) 3) State movement under the VCS (**Section 3.2.2**)
3) Unstable travelling	1) Minimum safe distance or acceleration/deceleration rate is fixed. 2) Trains could not be transferred to convoy state.	1) Introducing state movement for transferring trains into the convoy state (**Section 3.2**). 2) Proposing equation to calculate optimal acceleration/deceleration rate (**Equation (3-13)** and **(3-14)**).
4) Unsafe when splitting from a train convoy	1) a following start splitting too late 2) More than two trains will split out.	1) Introducing optimal splitting point (**Section 3.2.2.2**). 2) Proposing the state movement controlling trains passing a junction (**Figure 3.9**)

4.4 Test cases 1: Proceeding as a train convoy

In one peak-hour operation, 20 trains depart from station A maintaining 3 min headway time. They have operated along 250 km route from station A directly to station B (**Figure 4.1**). Assuming that every two trains will be built into the same convoy (10 pairs of trains) by using the operational parameters shown in **Table 4.2**. The trains will start to be merged into a convoy immediately after departing from station A and will operate based on the proposed approach introduced in **Section 3.2.2**.



* Trains operate under normal conditions (i.e., no impact from weather and track elevation)

Figure 4.1 Test case: Example 1

Assuming that the velocity difference between trains in the merging state is 5 m/s. Thus, the leading and following trains will accelerate to 55 m/s and 60 m/s respectively for merged into a convoy.

Table 4.2 Operational parameters used in the simulation

Parameters		
1) Velocity limit (v^{max}) along the route	70	m/s
2) Optimal velocity (v_k)	60	m/s
3) Velocity limit at junction (v^{maxp})	30	m/s
4) Merging velocity difference (Δv_k^{mer})	5	m/s
5) Splitting velocity difference (Δv_k^{spt})	5	m/s
6) Leading train's merging velocity	55	m/s
7) Time step (Δt)	10	sec
8) Safety margin (SM)	2.4	km
9) Maximum acceleration rate (a_k^{max})	0.5	m/s^2
10) Maximum deceleration rate (b_k^{max})	0.5	m/s^2
11) Junction operation time (T^{pnt})	12	sec
12) Converging junction position (x^{cvr}) (measured from station B)	50	km
13) Diverging junction position (x^{dvr}) (measured from station B)	2	km
14) Train length (l_k)	100	m
15) Permissible headway time under the MBS	3	min

They will be split from a convoy when a following train reaches the diverging junction placed at 2 km from station B.

Table 4.3 Safety margin for VCS

Elements	Time (sec.)	Detail
1) Train system (ETCS)	4	ETCS response and brake actuation time
2) Driver response	6	Time that the driver responses to the displayed data to operate the control
3) Train protection system	4	Time due to overlap space between EoA and SvL and the position detection tolerance
4) Driver assisting response	3	System operation time (Time to input data to display at the user interface)
5) Data transmission	5	Data transmission time from a train to the RBC
6) Euro-balise spacing	5	Delay time caused by positioning detection system (Euro-balise has been installed in every 500 m.)
7) Movement authority (MA)	7	Time of MA process (evaluating, transmitting, and sending back to the train)
Total	**34**	**SM = (34 sec. x 70 m/s.) ≈ 2.4 km**

The elements calculated the safety margin (SM) is shown in **Table 4.3**. The safety margin (SM) used in the VCS can be the same as used in the MBS (Quaglietta & Goverde, 2019b). In this test, approximately 2.4 km safety margin is added into the minimum safe distance equation under both MBS and VCS.

4.4.1 The simulation results

Assuming that every convoy within the defined time period has been built by using the same operational parameters. The velocity-time and velocity-distance profiles of both the leading and the following trains are simulated based on the proposed state movement conditions.

4.4.1.1 The leading train

The simulated velocity profile of the leading train or the first train in each convoy is shown in **Figure 4.2**. The leading train accelerates to 55 m/s after departing from station A to allow the following train catching up with 60 m/s. It has proceeded by constant velocity at 55 m/s through the merging state and then accelerate to 60 m/s suddenly after transferred to the convoy state. It decelerates from 60 m/s to 40 m/s when it reaches 130 km. Then, it operates by 40 m/s for 20 km before accelerating to 50 m/s. after that, it proceeds by constant velocity at 50 m/s for 15 km before decelerating to 45 m/s.

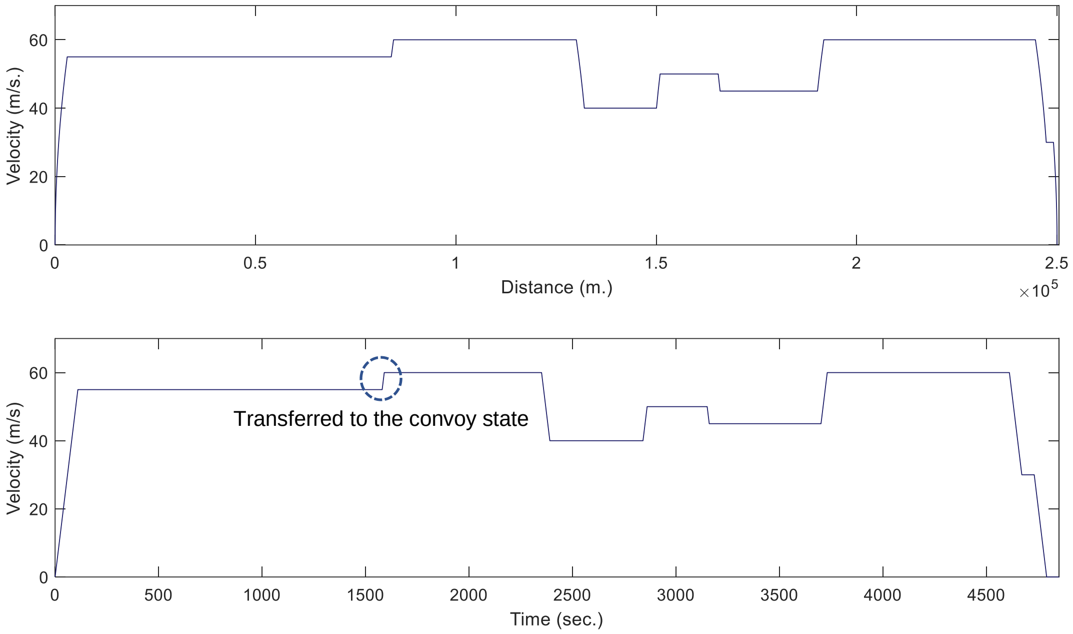


Figure 4.2 Velocity profile of the first train (the leading train) in the convoy

Then, when it reaches 190 km, it will accelerate again to 60 m/s and operate by constant velocity before decelerating to 30 m/s for passing a diverging junction. After that, it decelerates again by 0.5 m/s^2 braking rate for stopping at the station B.

4.4.1.2 The following train

The velocity-time and distance-time profiles of a couple of trains built into the same convoy are shown in **Figure 4.3**. With 5 m/s merging velocity difference (Δv_1^{mer}), the following train 2 accelerates to 60 m/s after dispatched from station A to be merged into the same convoy with the leading train 1. As a higher velocity of the following train 2, the distance separated from the leading train 1 has been decreased until equal to (or less than) the minimum safe distance required in the merging state. Then, the following train 2 is forced to decelerate to the same velocity as its leading train at 55 m/s (red dotted circle at time 1570 sec) transferring both trains into the convoy state.

The velocity profile of a couple of trains during the convoy state (Time between 1580 – 4330 sec.) is shown in **Figure 4.4**. It is obviously seen that the following train 2 has proceeded in relation to the movement of the leading train 1. When the leading train 1 decelerates from 60 m/s to 40 m/s (time between 2350 – 2390 sec), the following train 2 is forced to decelerate from 60 m/s to 40 m/s as well. It is not forced to decelerate at the same time as its leading train (blue dotted circle) due to communication time (Δt). However, it could be guaranteed that the distance between trains is not less than the minimum safe distance. This is because an additional term is added into the minimum safe distance equation in order to prevent unsafe situation in the case that a leading train decelerates when it is in the convoy state (See more detail in the **Section 3.1.1.2**).

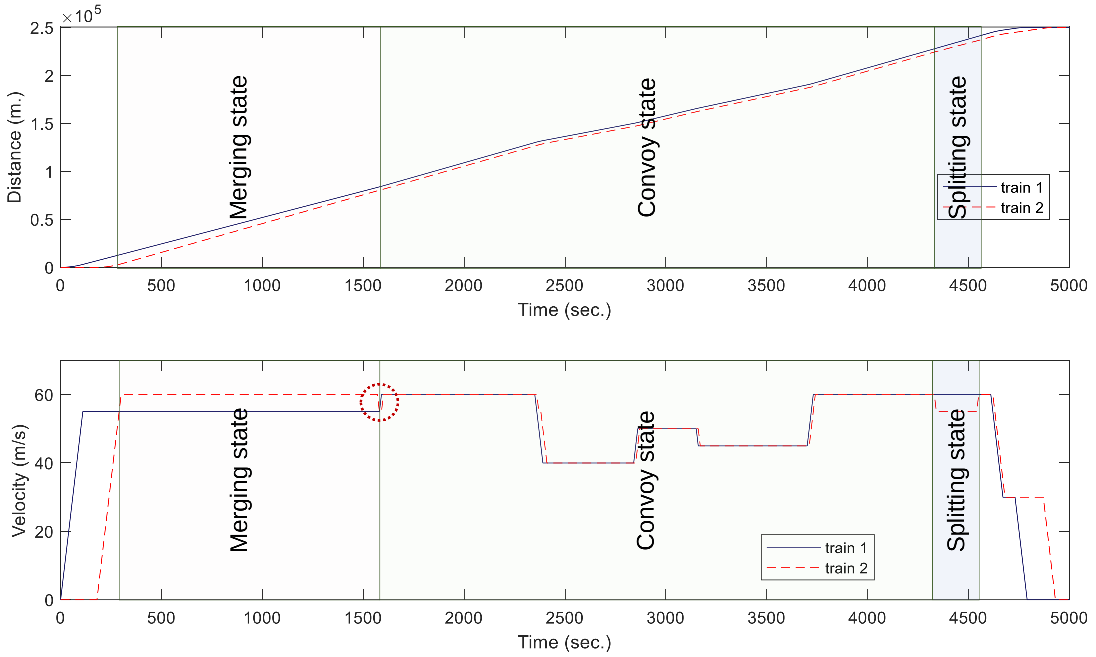


Figure 4.3 Distance and velocity profile of a couple of trains operating under the proposed approach

When the leading train 1 accelerates from 40 m/s to 50 m/s (time between 2840 - 2860 sec), the minimum safe distance between trains is updated and increased. This condition will force the following train 2 to accelerate instantly from 40 m/s. to 50 m/s transferring both trains to the convoy state again (time between 2870 – 3150 sec). Similar to the movement during the time between 3700 and 3730 sec, the following train is stimulated to accelerate from 45 m/s to 60 m/s according to the acceleration of the leading train 1.

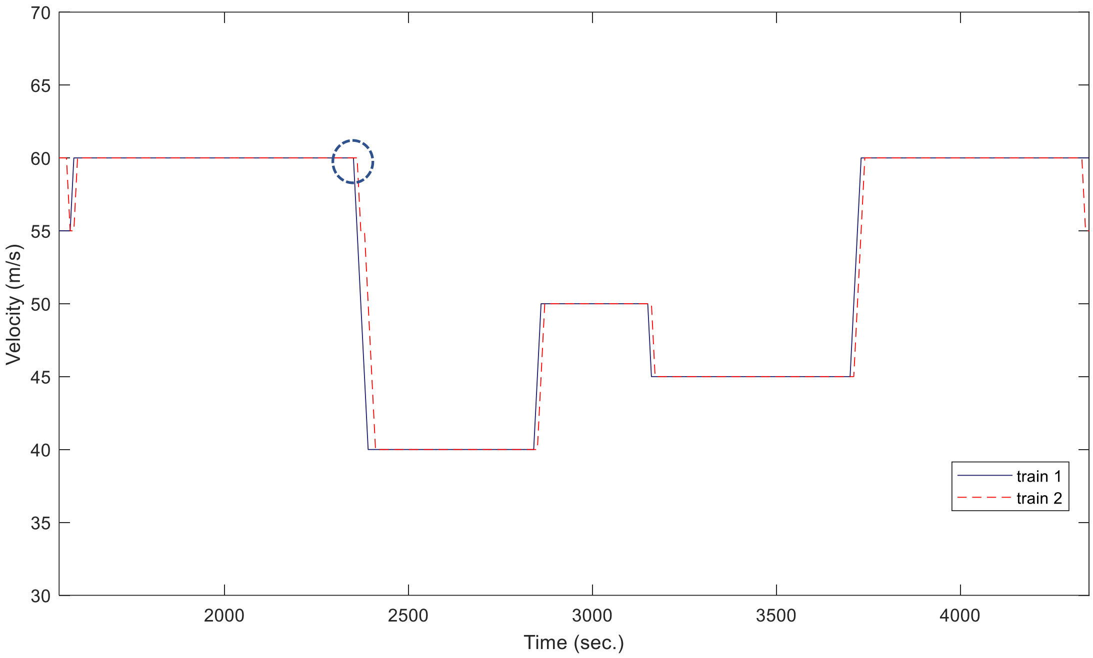


Figure 4.4 Velocity profile of a couple of trains during the convoy state

Thus, it could be concluded that the proposed approach can be applied for controlling following train movement effectively. A following train operates in relation to the movement of its leading train for minimizing and maintaining safe distance separated from a leading train.

4.4.2 The effectiveness of the proposed approach

Four aspects including capacity, safety, movement stability, and range of simulated acceleration are determined in order to evaluate the effectiveness of the proposed approach.

4.4.2.1 Capacity

In this test, each pair of two trains are built into the same convoy and the first train in each convoy still operates under the MBS. Thus, the headway time from the first train in a convoy and the last train in the convoy ahead is at least the minimum headway time under the MBS (Δt^{MBS}). Assuming that trains in each convoy have operated by the same operational parameters. Thus, the average headway time between trains in an hour can be calculated by

$$\Delta t^{avr} = \left(\Delta t_k^{sht} + \Delta t^{MBS}\right)/N \tag{4-1}$$

where

Δt_k refers to the shortest headway time between trains in the same convoy that can be computed by $\Delta t_k = \frac{\Delta x_k(t)+l_k}{v_{k+1}(t)}$

N is the number of trains built into the same convoy

Assuming that the minimum permissible headway time under the MBS (Δt^{MBS}) is 180 sec. Thus, in one-hour time period, 20 trains, at maximum could operate along the same route. The separation distance between trains when trains have operated under the proposed approach is shown in **Figure 4.5**. It is seen that the separation distance between trains when they have been within the convoy state directly depends on the operating velocity of a train convoy.

Immediately after transferred into the convoy state, the leading train 1 accelerates from 55 m/s to 60 m/s forcing the following train 2 to accelerate to the same velocity. The distance between them is increased from 3525 m to 3550 m. It is reduced to 3200 m when velocity of the train convoy is decreased from 60 m/s to 40 m/s. Due to the deceleration of the train convoy, the headway time between trains is increased from 61 sec to 83 sec. Thus, the route capacity is decreased from 29 to 27 trains/hour.

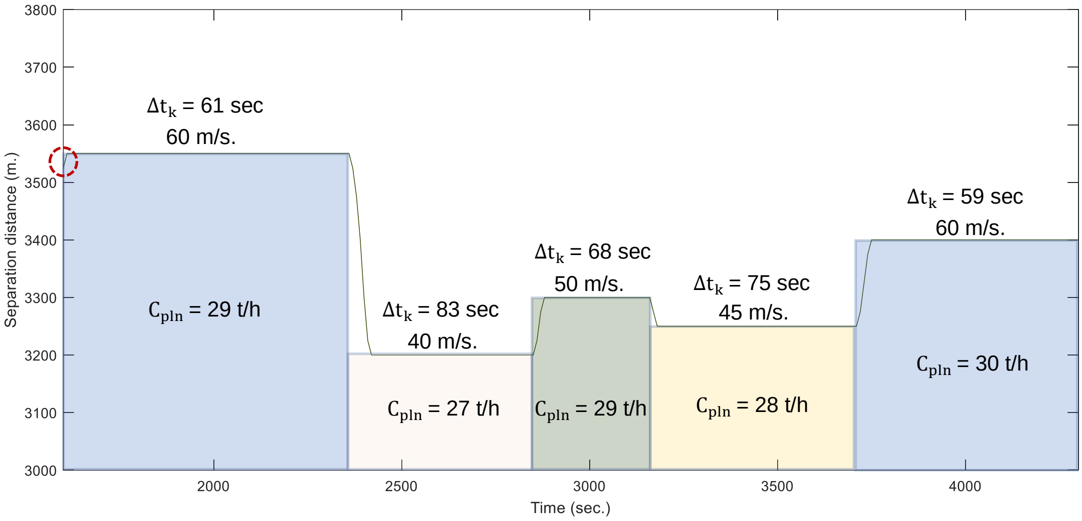


Figure 4.5 Separation distance between trains under the proposed approach

The distance between trains is increased to 3300 m when the train convoy's velocity is increased to 50 m/s. It is decreased to 3250 m when a couple of trains decelerates from 50 m/s to 45 m/s. Then, it is increased to 3400 m when velocity of both trains is increased to 60 m/s.

The shortest headway time between trains in the same convoy is 59 sec. Therefore, the maximum theoretical number of trains under the VCS in the case that 2 trains is built as a train convoy is 30 trains per hour. 10 additional trains or 50% of the number of trains are increased compared to the capacity under the MBS. It is noted that it is the theoretical maximum number of trains in the case that every two trains are built into the same convoy using the same assumed operational parameters. However, the capacity can be different depending on many parameters such as the number of trains in a convoy, braking capability, etc.

4.4.2.2 Safety

The comparison between the simulated and the minimum safe distance is shown in **Figure 4.6**. It is obviously seen that the actual separation distance between trains is mostly longer than the minimum safe distance. Excepting the different distance during time between 2370 – 2410 sec and at 3170 sec (blue dotted circles), the simulated 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. However, it could be guaranteed that the trains still operate safely because the minimum safe distance used in the proposed approach is modified. The additional term is added to prevent unsafe movement in the case that a leading train decelerates while proceeding during the convoy state (See more detail in **Section 3.1.1.2**).

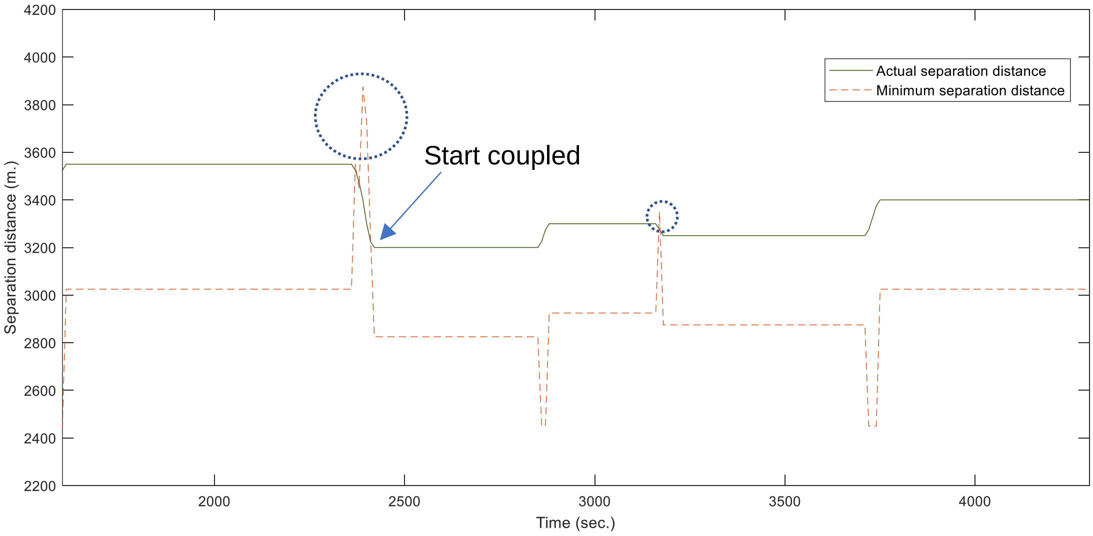


Figure 4.6 Comparison between the simulated and minimum safe distance between trains during the convoy state.

4.4.2.3 Realistic acceleration rate

According to the simulated acceleration of a couple of trains shown in **Figure 4.7**, it is obviously seen that the acceleration rate of the following train 2 varies within the limited range between -0.5 and 0.5 m/s^2. Thus, the acceleration/deceleration rates obtained from the proposed approach does not exceed than the maximum rate of a train.

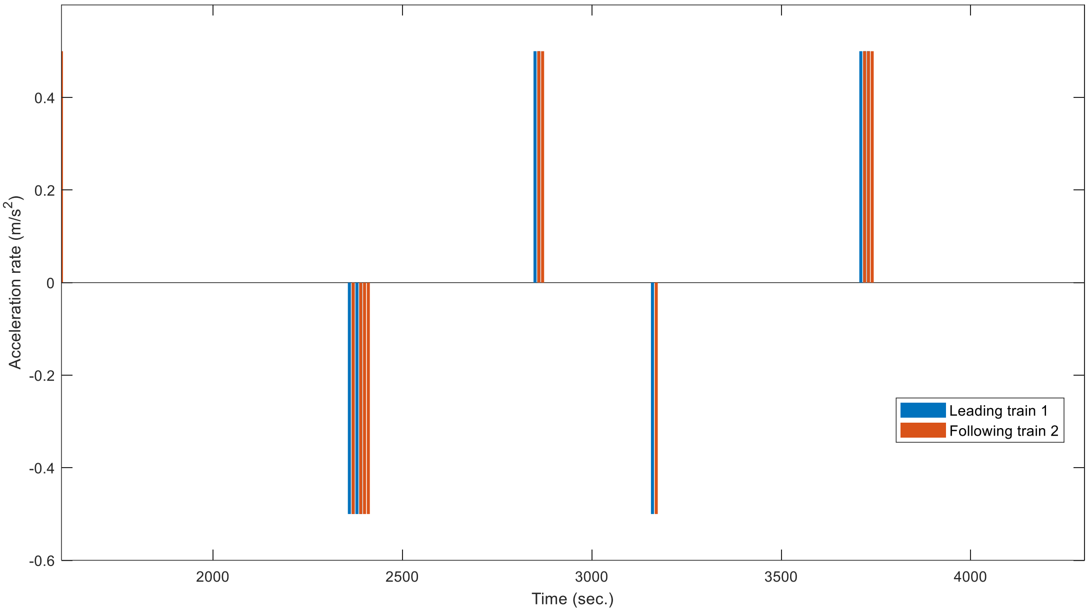


Figure 4.7 Variation of acceleration rate during the convoy state (max. acceleration rate = 0.5 m/s^2, max. deceleration rate = 0.5 m/s^2)

Figure 4.8 shows the simulated result in the case that the maximum acceleration/deceleration rate of the following train is lower than the maximum rate of the leading train. Assuming that the maximum deceleration and acceleration rate of the following train is -0.3 m/s^2 and 0.3 m/s^2 respectively. It is obviously seen that rates of acceleration/deceleration computed from the proposed approach are in the limited range. When the following train 2 is forced to be transferred into the convoy state, its velocity must be decreased from 60 m/s to 55 m/s. It firstly decelerates by 0.3 m/s^2 reducing velocity from 60 m/s to 57 m/s. Due to the decrease of velocity difference between trains, the minimum safe distance between them is also decreased. As a result, the following train could operate by constant velocity at 57 m/s until the distance separated from the leading train is equal to or shorter than the updated minimum safe distance (green dotted circle in **Figure 4.8**). Then, it is stimulated to decelerate again by 0.2 m/s^2 reducing velocity from 57 m/s to 55 m/s in order to be coupled as the same convoy with the leading train.

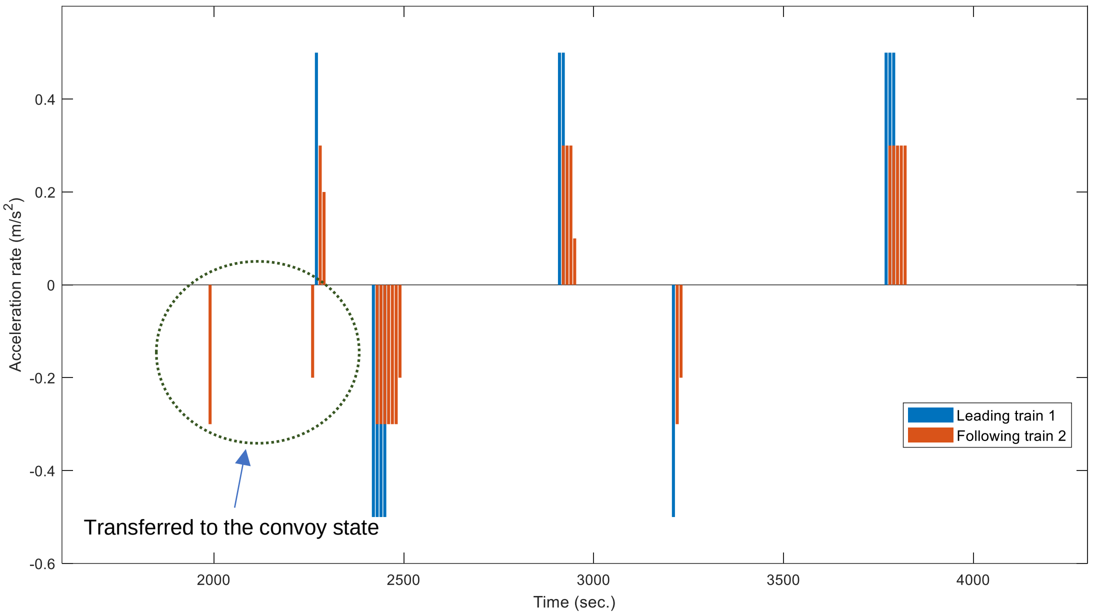


Figure 4.8 Variation of acceleration rate during the convoy state (max. acceleration rate = 0.3 m/s^2, max. deceleration rate = 0.3 m/s^2)

4.4.2.4 Stability

The variation of amplitudes of headway distance during the merging state (time between 180 - 1570 sec) are plotted in relation to the merging velocity gap as shown in **Figure 4.9**. It is seen that the headway distance has gradually been decreased as a higher velocity that the following train 2 catches up with the leading train 1.

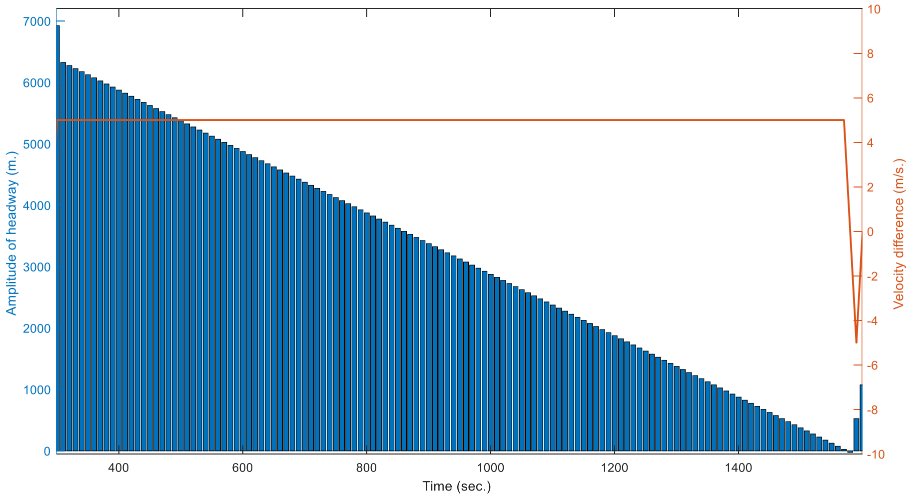
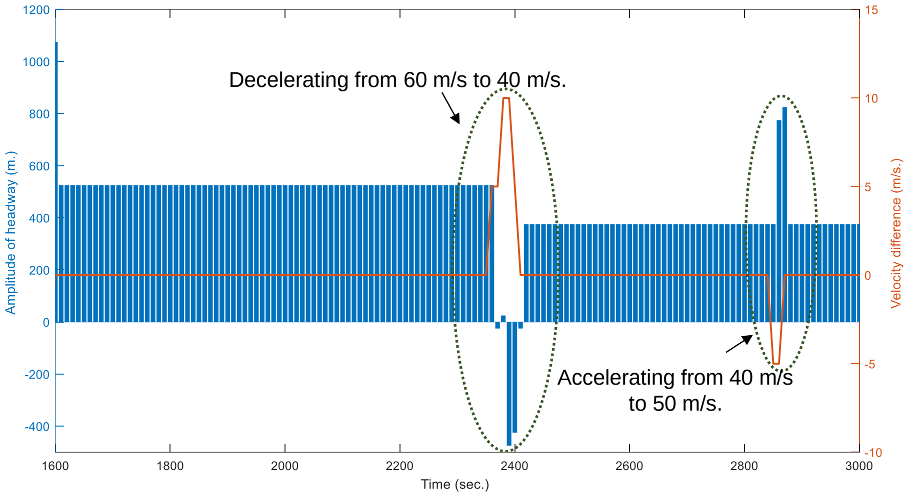
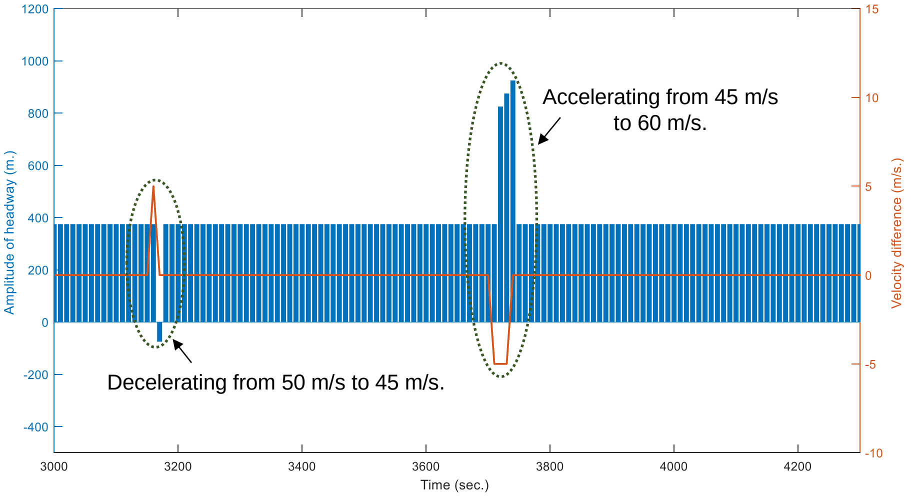


Figure 4.9 Amplitude of headway distance during the merging state

After transferred into the convoy state (time between 1580 – 4300 sec in **Figure 4.10**), the amplitude of headway distance between trains has been stable at 525 m. it is reduced to 375 m when the operating velocity of a train convoy is decreased from 60 m/s to 40 m/s. It has been stable at 375 m before increased to approximately 800 m for 10 sec when the leading train accelerates from 40 m/s to 50 m/s. Then, the following train is forced to accelerate to the same velocity as the leading train shortening the distance between them. As a result, the headway distance between successive trains has been maintained again. It could be said that the following train cannot obtain stable travelling only for a very short time period when transferred into the convoy state. Thus, the proposed approach could help a following train obtaining stable travelling, in which the distance separated from a front train has been maintained.



(a) between 1600 – 3000 sec.



(b) between 3000 – 4300 sec.

Figure 4.10 Amplitude of headway distance during the convoy state

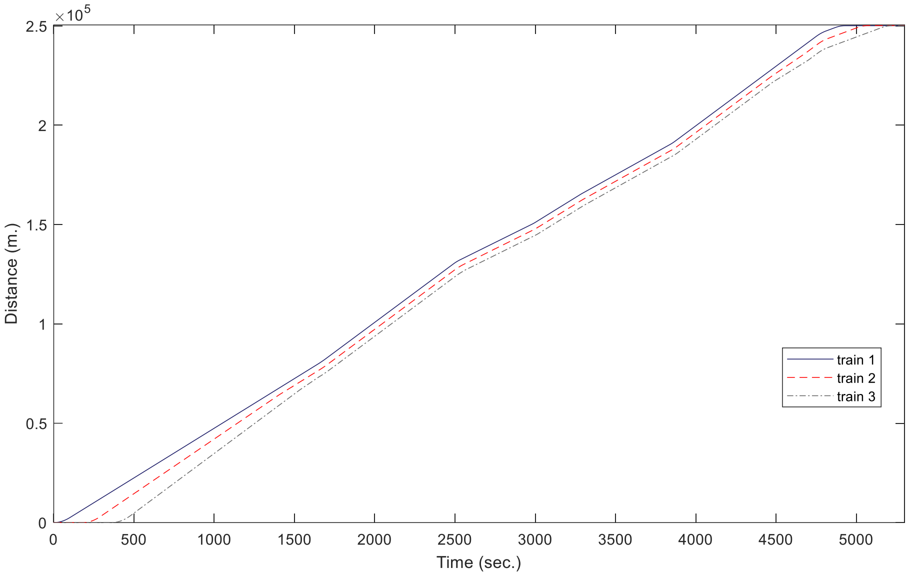
To sum up, the proposed approach could be applied for controlling following trains operating under the VCS effectively. The route capacity is increased in that the maximum number of trains under the VCS that can operate along the same route is higher than maximum number of trains under the MBS. It could be confirmed that the trains have operated safely, in which the separation distance between trains is longer the minimum safe distance. The safety aspect is improved because the acceleration and braking rate calculated from the proposed approach does not exceed than the maximum acceleration and braking capability of a train. In addition, the train could obtain stable travelling. A following train will catch up with a leading train and split out from a train convoy by using constant velocity. The velocity and distance between trains has been maintained during the convoy state.

4.5 Test case 2: Building more than two trains into a train convoy

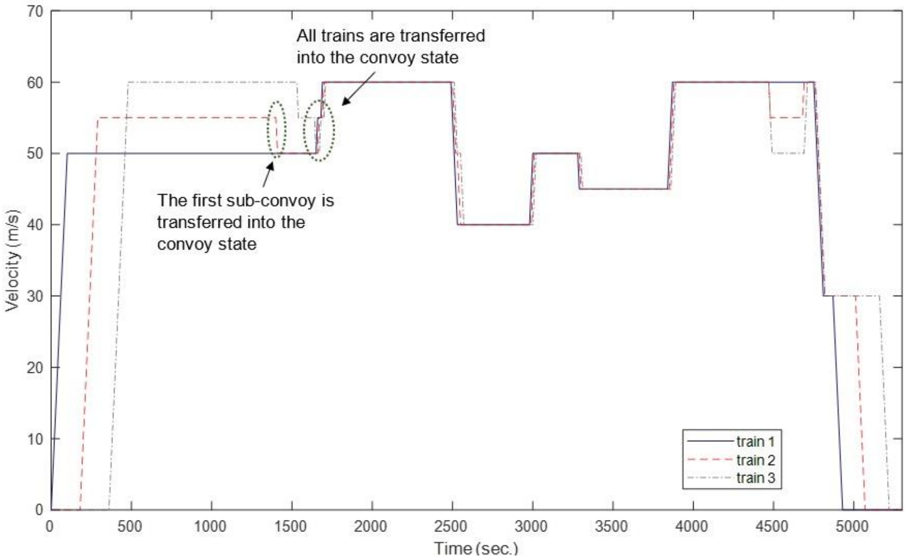
The proposed approach in the Section 3.2 can also be used to build more than two trains into the same convoy. Te **Figure 4.11** shows the distance and velocity profile of three trains built into the same convoy using operational parameters shown in **Table 4.2**. Assuming that three trains are merged into the same convoy. The train 2 and train 3 proceed by 55 m/s and 60 m/s respectively for catching up with the train 1 that operate by 50 m/s. There are two couples of trains in the same train convoy.

The train 1 and train 2 are firstly transferred into the convoy state due to a longer merging time period. The train 2 is forced to decelerate from 55 m/s to 50 m/s in order to be transferred into the same convoy with the train 1. After transferred into the convoy state, the train 1 and train 2 have operated by the same velocity at 50 m/s. When the distance between the train 3 and the train 2 is shorter than the minimum safe distance, the train 3 is forced to decelerate by 0.5 m/s^2 from 60 m/s to 55 m/s. Then, it could operate by 55 m/s for a short time period due to the deceleration of minimum safe distance. Then, the train 3 is forced to decelerate again from 55 m/s to the same velocity as two front trains transferring all three trains into the convoy state.

As shown in **Figure 4.11 (b)** during the time between 1760 – 4450 sec, it is obviously seen that following train 2 and train 3 have operated in relation to the movement of the first train (train 1) in the train convoy. They accelerate when the train 1 accelerates, decelerate when the train 1’s velocity is decreased, and operate by constant velocity if the train 1’s velocity has been stable.



(a) Distance profile of three trains



(b) Velocity profile of three trains

Figure 4.11 Distance and velocity profile of three trains built into the same convoy

4.6 Test case 3: Passing a converging and diverging junction

Figure 4.12 shows the test case to determine the effectiveness of the proposed approach. The converging and diverging junction are placed at 50 km and 2 km from the station B. Assuming that two successive trains are merged into a train convoy and split out from a convoy by using same merging pattern. Thus, the separation distance between trains in every convoy at the same position is also the same.

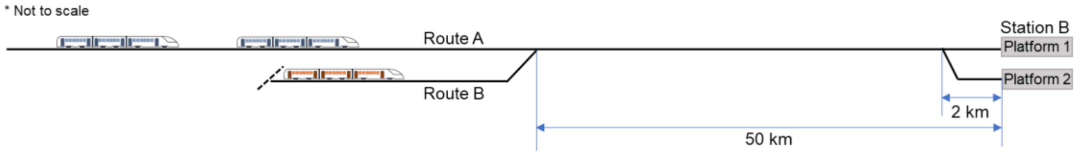


Figure 4.12 Test case: Example 2

The simulated velocity - distance profile of a train convoy is shown in **Figure 4.13**. Two trains have been built into a train convoy by 5 m/s velocity difference covering approximately 85 km to transfer them into the convoy state. It is assumed that a train from other route will be inserted between the convoys by keeping the permissible headway time from the train on the main route. Thus, the average headway time between trains when passing a converging junction (Δt_{cvr}^{avr}) can be computed by using **Equation (4-2)**.

$$\Delta t_{cvr}^{avr} = \left(\Delta t_{k}^{cvr} + \Delta t_{N}^{MBS} + \Delta t_{m}^{MBS}\right)/(N+1) \tag{4-2}$$

where

Δt_{k}^{cvr} refers to the headway times between trains in the same convoy when passing a junction.

Δt_{m}^{MBS} is the minimum headway time from the inserted train (m) to the first train in a convoy.

Δt_{N}^{MBS} is the minimum headway time from the last train in a convoy (N) to the inserted train (m).

N is the number of trains built into the same convoy

According to the simulated result shown in **Figure 4.14**, the headway time between trains when passing the converging junction is 60 sec. It is assumed that an inserted train from route B is inserted between successive convoys on the main route by keeping at least 180 min away from the trains on the main route. Therefore, the theoretical maximum number of trains passing the converging junction is $C_{cvr}^{max} = \frac{3600}{(60+180+180)/3}$ = 25 trains/hour

With 180 sec minimum permissible headway time, the maximum number of trains under the MBS is only 20 trains per hour as there is no additional trains from other route could be inserted into the route. If trains are built into a train convoy, the distance between convoy is increased allowing more trains being inserted. Thus, it could be concluded that building trains as a train convoy could increase capacity at a converging junction.

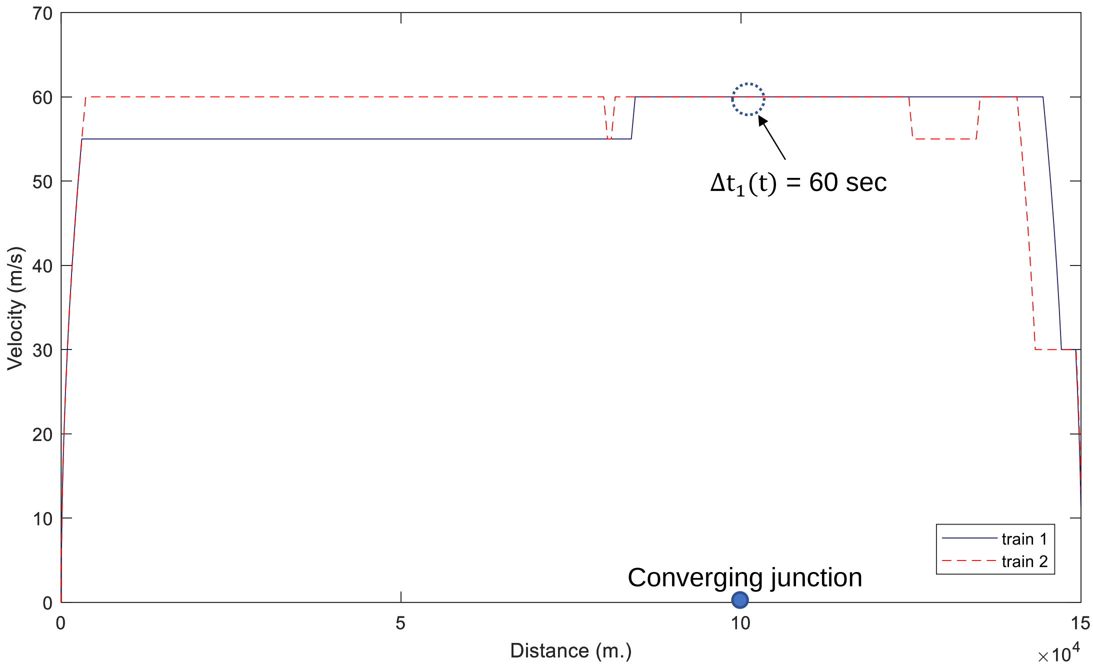


Figure 4.13 Simulated velocity - distance profile of a train convoy when passing a converging junction.

The comparison between the simulated separation distance and the minimum safe distance at the converging junction is shown in **Figure 4.14**. It is found that the distance between trains when passing the junction is 3550 m. It is obviously longer than the minimum safe distance required for passing the junction at 3025 m.

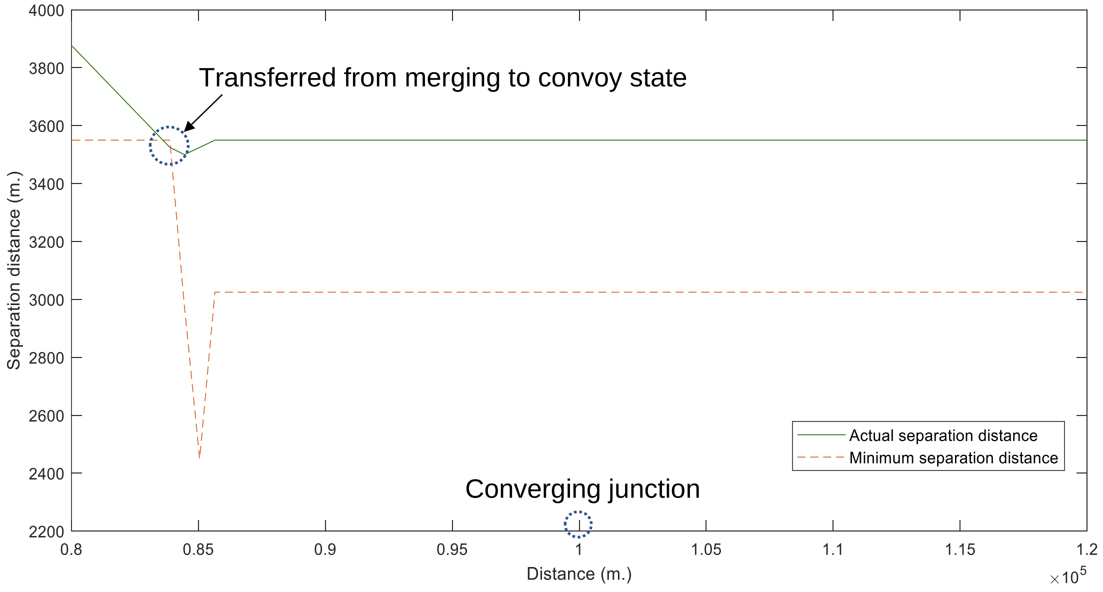


Figure 4.14 Comparison between the simulated separation distance and minimum safe distance at the converging junction

Excepting the distance difference within blue dotted circle, the simulated separation distance is slightly shorter than minimum safe distance. However, it is ensured that the trains have operated safely because the additional distance is added into the minimum safe distance equation for improving safety during the transition state.

Assuming that both trains in the same train convoy will stop at different platforms at the station B. They will diverge and then proceed on different routes after passing the diverging junction placed at 2 km away from the station B. When trains operate in the convoy state, the separation distance between trains is 3550 m (approximately 60 sec headway time) but, the minimum safe distance required for passing through the diverging junction is 3760 m or about 126 sec. Thus, the distance between trains must lengthened before passing the junction. Using the approach in **Section 3.2.2.2** to split out from a train convoy when reaching the splitting point. The average headway time between successive trains when passing through a diverging junction could be expressed by **Equation (4-3)**.

$$\Delta t_{dvr}^{avr} = \left(\Delta t_{k}^{dvr} + \Delta t^{MBS}\right)/N \tag{4-3}$$

Where Δt_{k}^{dvr} refers to simulated headway time between successive trains in the same convoy when passing a diverging junction.

Figure 4.15 shows the simulated velocity – distance profile of a train convoy when approaching the station B. It is seen that the leading train has proceeded by constant velocity at 60 m/s while the following train has operated by a lower velocity at 55 m/s for lengthening the distance between them. When the distance between trains becomes longer than minimum safe distance under the MBS, the following train will be forced to accelerate to the same velocity as the leading train (green dotted circle). Then, both trains will decelerate from 60 m/s to 30 m/s for passing through the diverging junction. After splitting, both trains still operate under the VCS. The signaling control will be switched back to the MBS when the leading train passed the junction. According to the simulated distance between trains shown in **Figure 4.15**, the simulated headway time between trains when passing the diverging point is 140 sec. Thus, the theoretical maximum number of trains that could pass the diverging junction in an hour is

$$C_{dvr}^{max} = \frac{3600}{\left(\Delta t_{dvr}^{avr} + \Delta t_{N}^{min}\right)/2} = \frac{3600 \times 0.70}{(140 + 180)/2} = 22 \text{ trains/hour}$$

It can be concluded that the VCS could be applied to increase capacity. The route capacity in terms of the maximum number of trains that could pass a diverging junction is increased compared to the capacity under the MBS.

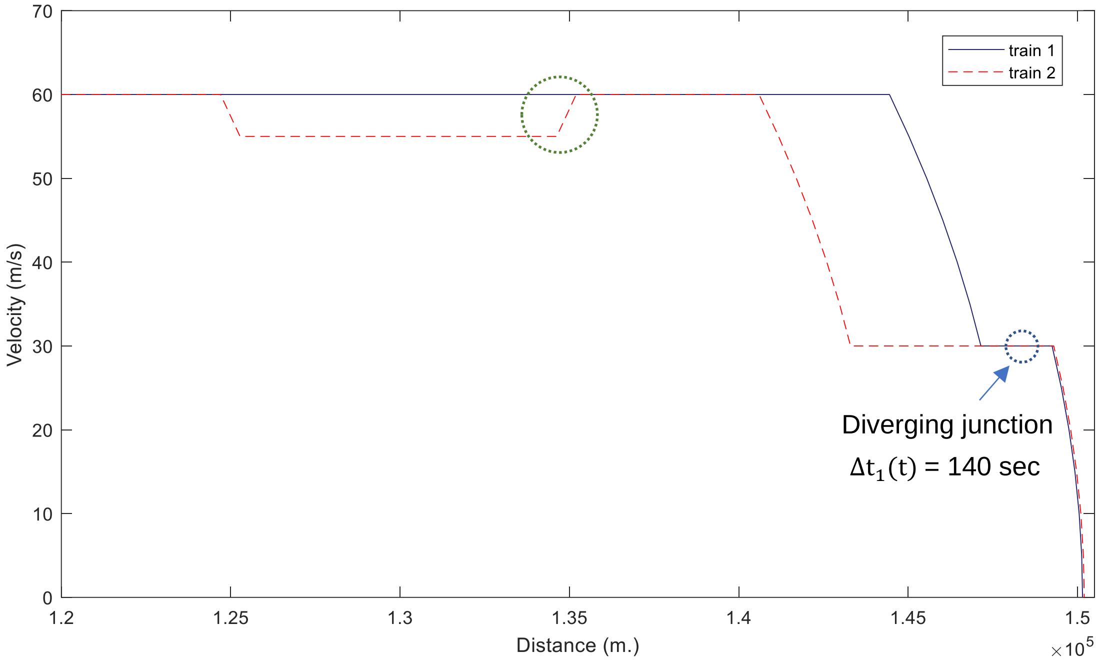


Figure 4.15 Velocity-Distance profile when passing a diverging junction

The comparison between simulated separation distance and minimum safe distance between trains when approaching the diverging point is shown in **Figure 4.16**. It is seen that the separation distance between trains has been lengthened (blue dotted ellipse) until it is longer than the minimum safe distance at 3760 m. The distance between trains has been maintained at 4450 m before reduced to 4150 m when trains decelerate to 30 m/s. Thus, it could be confirmed that trains have operated safely as the simulated distance between trains is longer than minimum safe distance.

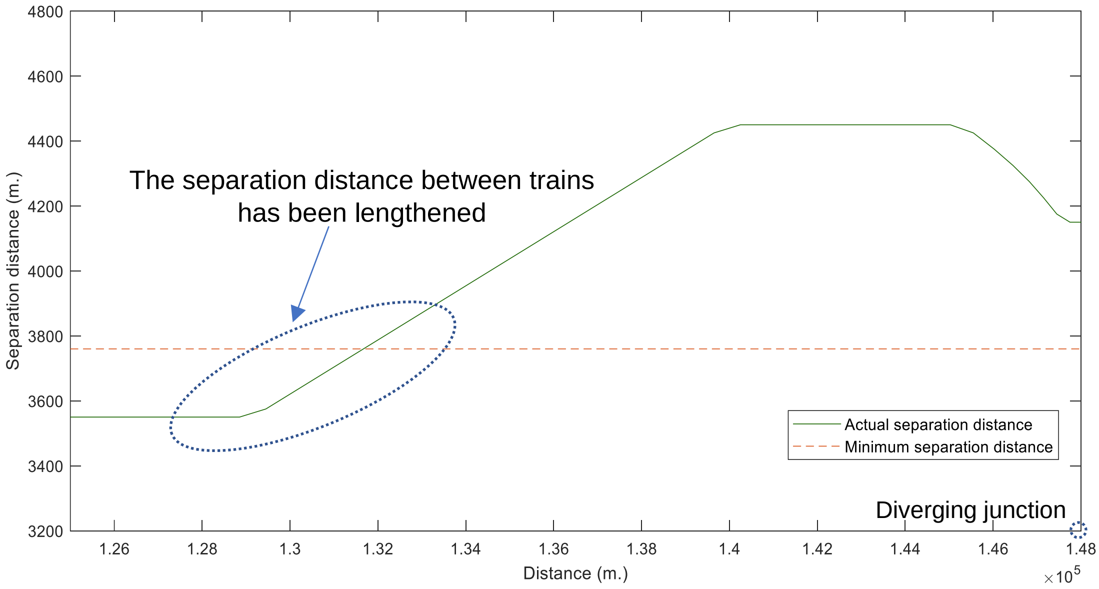


Figure 4.16 Comparison between simulated and minimum safe distance at a diverging junction

4.7 Summary

According to the simulation results, it is seen that a following train operates relative to the movement of its leading train. It will be merged into the same convoy with a leading train when the distance between them is equal to or becomes shorter than the minimum safe distance. When operating as a train convoy, a following train will accelerate if a leading train accelerates and will decelerate when a leading train slows down. When a train convoy is approaching a diverging junction, a following train will decelerate to a lower velocity than its front train to extend the safe distance separated from a leading train. It will start splitting out when reaching an optimal splitting point. Trains could operate as a train convoy passing a converging junction.

Compared to the operation under the MBS, the route capacity is increased, in which the distance between trains is close to the minimum safe distance. It could be ensured that trains could operate safely, in which the simulated distance between trains in a train convoy is longer than the minimum safe distance. In addition, it is obviously seen that a following train has operated smoothly and obtain stable travelling in throughout the operation under the proposed state movement. It is noted that it is the theoretical maximum number of trains in the case that each pair of two trains is built into the same convoy using the same assumed operational parameters. However, the capacity can vary depending on many parameters such as the number of trains in a convoy, braking capability, etc.

Chapter 5
Parameters impacting on route capacity

5.1 Introduction

Each signaling system has its own characteristic affecting the route capacity. A parameter which affects route capacity under the FBS might not affect the capacity of the route that is equipped with the other signaling controls. This is because the distance between trains under the FBS is separated by the block length while the separation distance under the MBS or the VCS could be reduced depending on real-time information of trains operating on the same route. There are many parameters that might affect route capacity. One obvious parameter relating distance between trains is the operating velocity. Operating by a higher velocity requires a longer distance away from a train in front. But the route capacity tends to be increased if travel time decreases, allowing more trains to operate. However, if operating velocity is extremely high, the route capacity might be decreased due to a higher headway time that trains will require when proceeding following each other (Dicembre & Ricci, 2011).

Not only the velocity of the train itself but also the velocity of an adjacent train affects the route capacity. When there is a mix of train types - e.g. low and high-speed trains - operating on the same route, capacity tends to be decreased. This is because if high-speed train follows a train proceeding with a lower speed, the following high-speed train cannot reach its maximum velocity. In the case that a low-speed train proceeds behind a high-speed train, the distance between them has been increased reducing the route capacity (M. Wang et al., 2012).

According to the simulated train movement under the VCS shown in the Chapter 4, it could be concluded that route capacity is higher than the capacity under the MBS. This is due to a shorter separation distance between trains, in which the successive trains in the same train convoy are separated by at least relative braking distance. Interestingly, the distance between trains might be different due to different values of an operational parameter. Referring to the simulated train movement in **Figure 4.5** in **Chapter 4**, the headway time between trains is different depending on the operating velocity. It is obviously seen that, after transferred into the convoy state, the headway time between successive trains is decreased as an increase in operating velocity resulting an increase in route capacity. Another example that results different capacity is when the number of trains built into a train convoy is different. The available time gap is increased with the increase of the number of trains in a convoy. In the other words, building more trains into the same convoy increases an unused capacity allowing more trains to be inserted into the same route. Because the main benefit from the VCS is to increase capacity, it would be better if we have to solution to build a train convoy more effectively.

The parameters that may impact route capacity are reviewed in **Section 2.6**. These parameters and additional parameters which may affect route capacity are determined in terms of whether and how they impact on route capacity. The route capacity in different values of each parameter is calculated using the UIC 406 (2013) method (**Section 3.3.1**). The percentage of capacity consumption of different values of each parameter is compared in order to determine whether a parameter affects route capacity. In addition, the capacity utilization in terms of number of trains, velocity deviation, heterogeneity, and travel time are compared for explaining how each parameter impacts route capacity (**Section 3.3.2**). In **Section 5.4**, the train movement under different values of 16 parameters is simulated. The outcome is used to create a guideline to create a good timetable, provide a better policy, and minimize costs of operation.

5.2 Objectives

The objective of this chapter is to determine whether and how a parameter affects route capacity. The rate of capacity consumption of different values is compared in order to determine whether a parameter affects route capacity. The rate capacity utilization (number of trains, velocity deviation, heterogeneity, and travel time) is compared for explaining how each parameter impacts route capacity. The results will be used as a guideline to create a train convoy more effectively.

5.3 Methodology

To determine the possibility to run more trains on the same route within the defined time period, it is important to know the percentage of capacity consumption under current service. The timetable compression method UIC 406 (**Section 3.3.1**) is used to calculate the percentage of capacity consumption and used to estimate the unused capacity. In addition, the capacity utilization (**Section 3.3.2**) in terms of number of trains (**Section 3.3.2.1**), velocity deviation (**Section 3.3.2.2**), timetable heterogeneity (**Section 3.3.2.3**), and punctuality (**Section 3.3.2.4**) are compared for explaining how each parameter impacts route capacity (**Section 3.3.2**).

Before applying the compression method to calculate the percentage of capacity consumption, the infrastructure (**Section 5.3.1**) and train timetable (**Section 5.3.2**) are created. Then, the route is divided into sections due to different signalling system, number of tracks, junctions, etc (**Section 5.3.3**). Then, the capacity utilisation in terms of the number of trains (**Section 5.3.4.1**), velocity deviation (**Section 5.3.4.2**), timetable heterogeneity (**Section 5.3.4.3**), and travel time (**Section 5.3.4.4**) are calculated for determining how a parameter affects route capacity.

5.3.1 Building track layout and defining the operational parameters

Assuming that the trains have operated under the normal conditions which has no impact from weather and track elevation. The trains within the defined time period proceed on double tracks route from station A directly to station B using the operational parameters shown in **Table 5.1**.

Table 5.1 Operational parameters

Parameters		
1) Velocity limit along main route (v^{max})	70	m/s
2) Optimal velocity (v^{opt})	60	m/s
3) Junction velocity limit (v^{maxp})	30	m/s
4) Time step (Δt)	10	Sec
5) Safety margin (SM)	2.4	km
6) Maximum acceleration rate (a^{max})	0.5	m/s²
7) Maximum deceleration rate (b^{max})	0.5	m/s²
8) Turnout switch operation time (T^{pnt})	12	sec
9) Station spacing (Δx^{total})	150	km
10) Converging junction position (x^{cvr}) (measured from station A)	50	km
11) Diverging junction position (x^{dvr}) (measured from station A)	148	km
12) Train length (l)	100	m
13) Inserted train length (l_m)	100	m

Two types of junctions; the converging and diverging junction are assumed to be placed at 50 km and 148 km away from the station A respectively (**Figure 5.1**). The trains proceeding on the main route can pass the converging junction by their optimal velocity at 60 m/s and will be forced to decelerate to v^{maxp} for passing through the diverging junction.

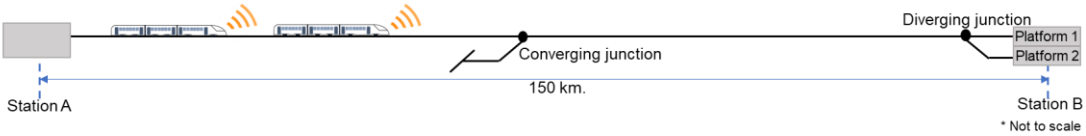


Figure 5.1 Track layout

The ideal distance-time and velocity-time profile of a train operating based on the operational parameters are shown in the **Figure 5.2**. A train departs from station A and then accelerate by 0.5 m/s^2 to its optimal velocity at 60 m/s. After that, it has operated by constant velocity passing through the converging junction. Then, it is forced to decelerate to 30 m/s when approaching the diverging junction. It has passed through the diverging junction by 30 m/s before decelerating again for stopping at the station B. The total time that a train has proceeded from station A to station B is 2650 sec.

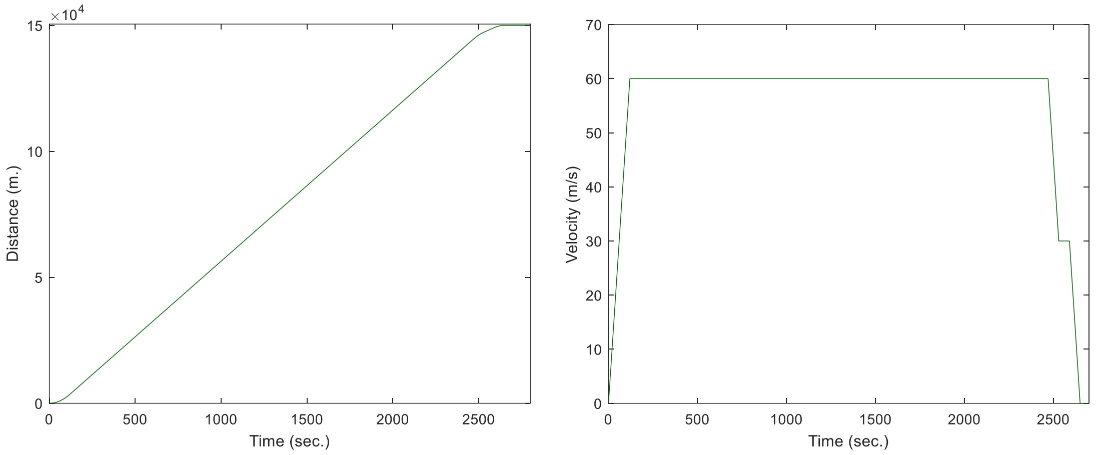


Figure 5.2 Ideal distance and velocity profile of a train on the main route

5.3.2 Creating timetable

In this test, it is assumed that when trains operate under the MBS, the percentage of capacity consumption is 100%, in which the successive trains are separated by the minimum headway time. Generally, when a train passes through a junction, it might be forced to decelerate for lengthening the distance separated from its front train. To prevent stop and go movement and prevent delay due to the deceleration of a train when passing through a junction, it is assumed that successive trains are separated by the minimum safe distance required at the converging junction. Thus, the minimum (critical) safe distance at the converging junction is used to be the minimum permissible headway time under the MBS.

The trains proceeding along the main route can pass through the junction by their optimal velocity. However, an extra train coming from another route could pass the junction by v^{maxp} at maximum. Referring to the safety margin under the VCS shown in **Table 5.1**, approximately 34 sec safety margin time is required for separating trains under the VCS. It is noted that the safety margin under the MBS is longer than the safety margin under the VCS due to communication time between a train and the control center, and the movement authority calculation time. Additional 10 sec is added to the safety margin required for the MBS. Thus, 44 sec safety margin time is used to calculate the minimum safe distance under the MBS.

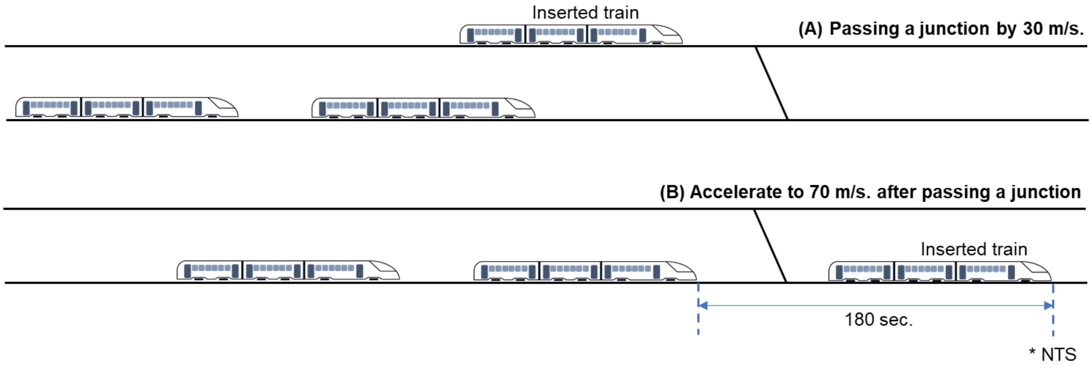


Figure 5.3 Minimum headway time between trains under the MBS

If an inserted train passes through the junction by 30 m/s, approximately 3.3 sec is spent to pass the junction by its whole length. It will accelerate to the maximum velocity restricted on the main route (70 m/s) after passing the junction (**Figure 5.3**). It will take another 80 sec covering 4 km for accelerating from 30 m/s to 70 m/s. For the same time period, the distance covered by a train proceeding through the main route is about 5.9 km. Thus, the braking distance should be expanded by Δx_m^{cvr} = 5.9 – 4.1 = 1.8 km. The minimum headway distance between trains at the converging junction is

$$\Delta x_1^{mcvr} = \left(\frac{(v^{max})^2}{2b_2^{max}} + SM\right) + (T^{pnt}v^{max}) + l_1 + \Delta x_m^{cvr}$$

$$\Delta x_1^{mdvr} = \left(\frac{(70)^2}{2(0.5)} + (44 \times 70)\right) + (12 \times 70) + 100 + 1800 = 10720 \text{ m.}$$

With 60 m/s operating velocity, the minimum headway time between successive trains operating under the MBS is approximately 180 sec (3 min).

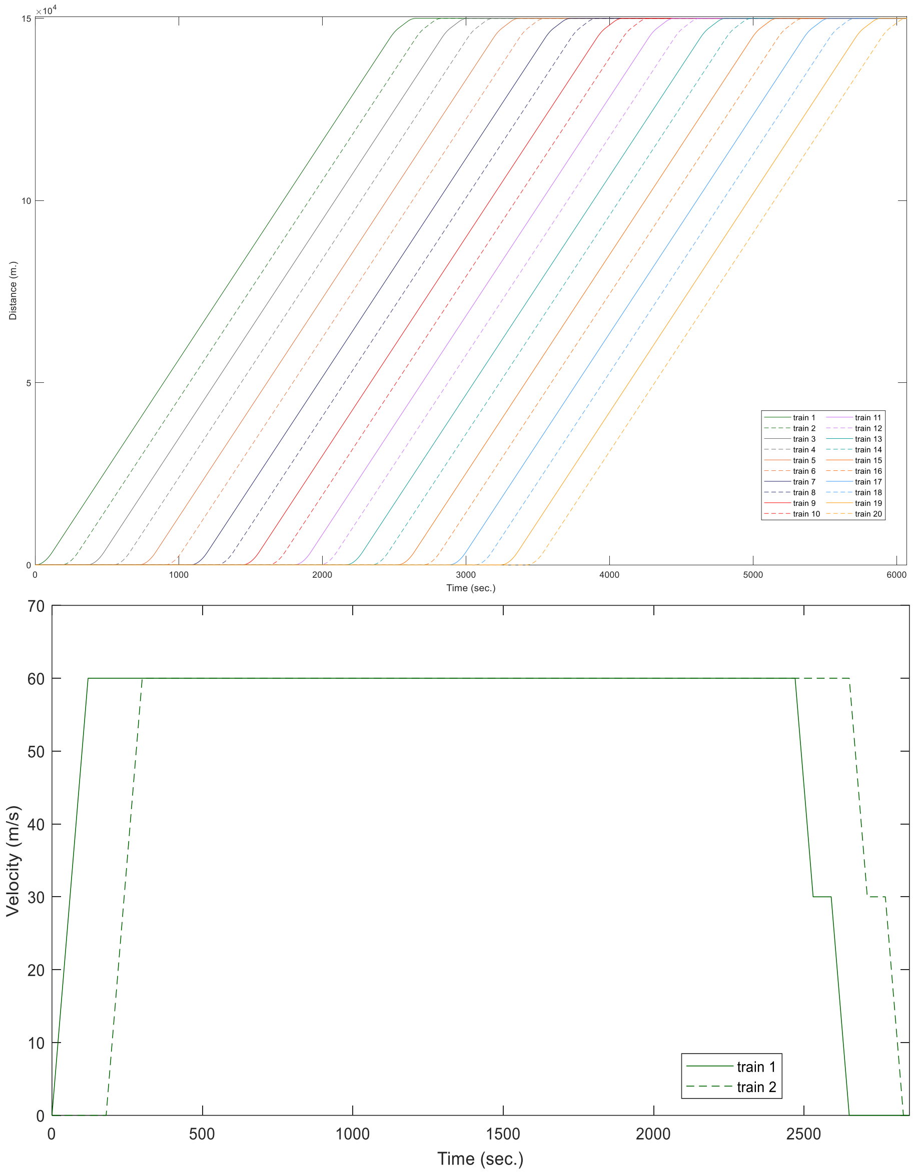


Figure 5.4 Simulated distance and velocity profile under the MBS

To maximize number of trains operating under the MBS in 1 hour defined time period, a train has to be separated from its front train by the minimum headway time. Assuming that the trains depart from station A maintaining 180 sec dispatching headway time. In one-hour time period, 20 trains can operate along the same route. The ideal distance-time and velocity-time profiles of trains under the MBS are shown in **Figure 5.4**. All trains operate using the same pattern by accelerating to their optimal velocity at 60 m/s and then proceeding by constant velocity passing through the converging junction. They decelerate to 30 m/s for passing the diverging junction and then decelerate again for stopping at the station B.

5.3.3 Dividing route into several sections

Following the suggestion by (UIC 406, 2013), the route should be divided into several sections. Each section ends when the signaling system is changed, the number of tracks is different, the number of trains is increased or decreased, timetable is change, etc. Referring to the track layout shown in **Figure 5.1**, the route can be divided into three sections due to the impact of crossing trains and the change of signalling control. The change of the number of trains and signalling control will occur at:

1) The converging junction, a train from other routes will be inserted increasing the number of trains operating on the section behind the junction.
2) The diverging junction, the trains diverge from each other. The number of trains after passing this point may be reduced.
3) The diverging junction, the signalling system will be switched back to the MBS after passing the diverging junction.

Thus, the route can be divided into three sections:

- **Section A**: from station A to the converging junction
- **Section B**: from converging junction to the diverging junction
- **Section C**: from the diverging junction to the terminal station B

In the section B (the distance from the converging to the diverging junction), the operational state of a train convoy will be switched from the merging or convoy state to the splitting state. It means that, within the Section B, the distance between successive trains has been decreased and then has been lengthened for passing through the diverging junction. Thus, the section B should be divided into two sub-sections due to the change of state of operational control. Based on the operational parameters in **Table 5.1**, the minimum separation distance required for passing the diverging junction (**Equation (2-7)**) is

$$\Delta \mathrm{x}_1^{\mathrm{mdvr}} = \left(\frac{(30)^2}{2(0.5)} + 2400\right) + (12 \times 30) + 100 = 3760 \text{ m.}$$

The possible minimum separation distance between successive trains when they are coupled as a train convoy (**Equation (3-17)**) is

$$\Delta \mathrm{x}_1^{\mathrm{pms}} = 2400 + \left(\left(\frac{1}{2}0.5(10)^2\right) + (30 \times 10)\right) = 2725 \text{ m.}$$

In the worst-case scenario, the separation distance between trains is ideally lengthened from the possible minimum separation distance at 2.72 km to minimum distance required for passing the diverging junction at 3.76 km. Thus, the separation distance between successive trains should be lengthened at least by 1035 m. With 5 m/s splitting velocity difference, a following train decelerates to 55 m/s for splitting from its leading train. The time to decelerate from 60 m/s to 55 m/s is 10 sec. For the same deceleration time period, the different travelling distance between two successive trains is 25 m. The separation distance between trains should be lengthened further for 1010 m. The total time used for extending the distance for 1010 m is 210 sec. Thus, the length of splitting zone (**Equation (3-23)**) is at least

$$\Delta x_k^{spt} = 60(10 + 210) = 13200\ \mathrm{m}.$$

In this test, the following train is forced to start splitting at the same point at 20 km away from the safe zone (1 km length of safe zone). Thus, the section B is divided into two zones including section B1 (from the converging junction to the splitting point) and section B2 (from the splitting point to the diverging junction). Therefore, the route is divided into four sections including section A, section B1, section B2, and section C as shown in **Figure 5.5**.

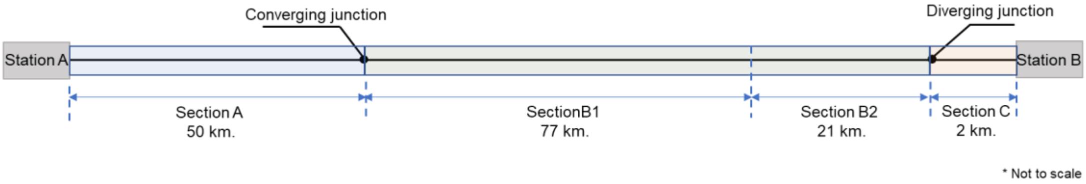


Figure 5.5 Divided sections for calculating capacity consumption

The distance-time profile of trains within one hour defined time period when trains operate under the MBS is shown in **Figure 5.6**. As the minimum headway time between trains under the MBS is 180 min, the capacity consumption of each section will result the same rate at 100%. The train timetable could not be compressed because the trains operate by maintaining 180 sec headway time away from their front train.

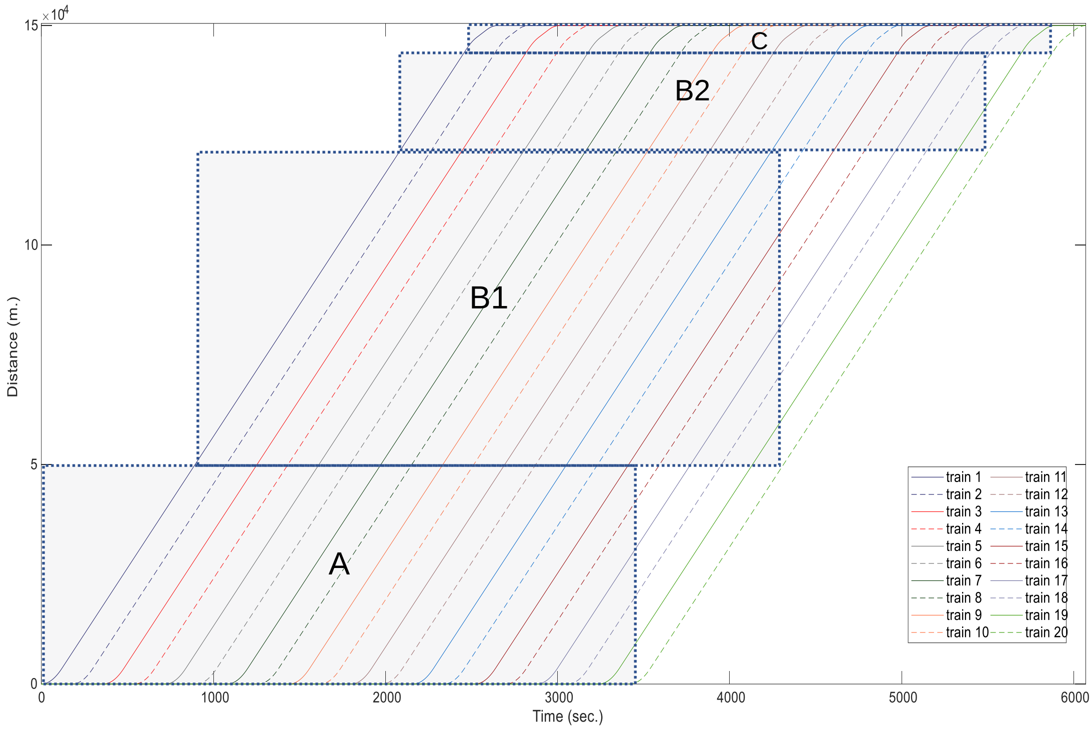


Figure 5.6 Distance-time profile of trains under the MBS

Figure 5.7 shows the example of simulated distance-time profile of trains under the VCS. It is seen that the distance between successive trains built into the same convoy has been decreased while the separation distance between successive convoys has been increased. The distance between successive convoys can be compressed increasing the percentage of unused capacity.

The timetable of the section A (from station A to the converging junction) cannot be compressed resulting the same rate of capacity consumption at 100%. Thus, in the station A, there is no relationship between the operational parameter and the rate of capacity consumption. The headway time between train 1 and train 2 and between train 2 and train 3 measured at the beginning of the section B1 is 110 sec and 250 sec respectively. At the end of the section, the headway time between train 1 and train 2 is reduced to 60 sec, which is equal to the minimum headway time under the VCS while the headway time between train 2 and train 3 is increased from 250 sec to 300 sec. Thus, the headway time between trains after compression measured at the beginning of the section B1 (**Figure 5.8 (b)**) is 110 sec and 180 sec.

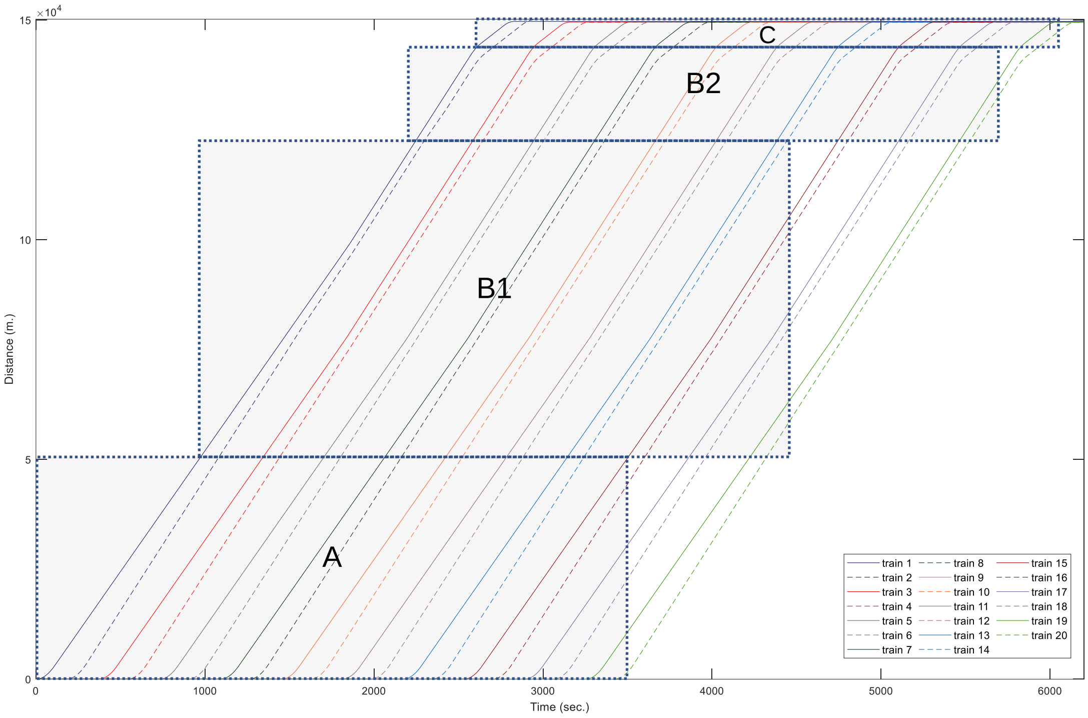


Figure 5.7 Distance-time profile of trains under the VCS

The percentage of capacity consumption (**Equation (3-34)**) of the section B1 is

$$\mathrm{CC}\ (\%) = \left(\frac{(180 \times 10) + (110 \times 10)}{3600}\right) \times 100 = 80.6\%$$

Thus, in the section B1, the unused capacity of the Section B1 is approximately 19%. Following the method to evaluate available capacity introduced by UIC 406 (2013), we need to add another one train a time and then re-calculate the percentage of capacity consumption again until it exceeds 100%. In this case, the available capacity in the section B1 can be calculate by

Adding the 1st train, $\mathrm{CC}\ (\%) = \left(\frac{(180\times11)+(110\times10)}{3600}\right) \times 100 = 85.6\%$

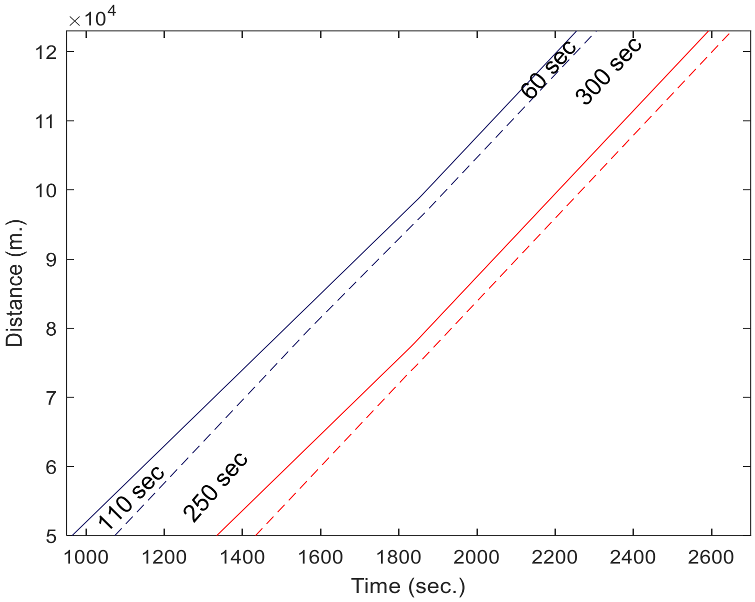
Adding the 2nd train, $\mathrm{CC}\ (\%) = \left(\frac{(180\times11)+(110\times11)}{3600}\right) \times 100 = 88.6\%$

Adding the 3rd train, $\mathrm{CC}\ (\%) = \left(\frac{(180\times12)+(110\times11)}{3600}\right) \times 100 = 93.6\%$

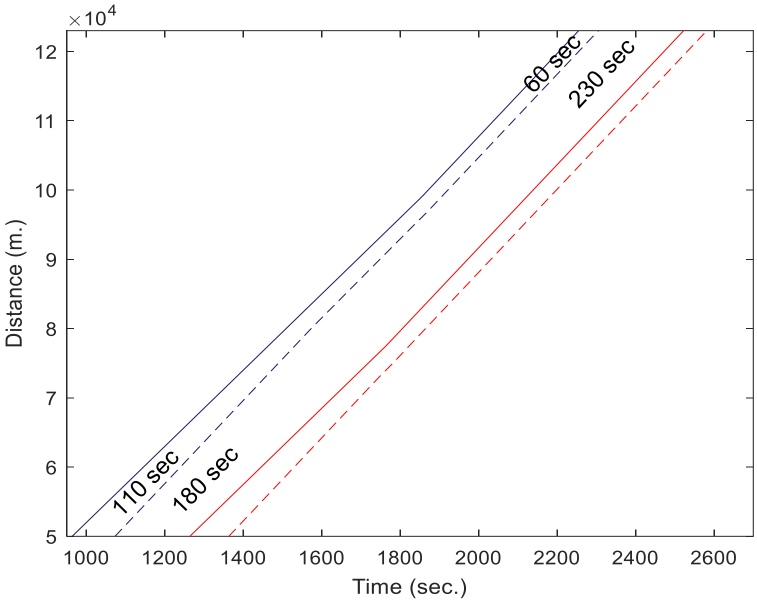
Adding the 4th trains, $\mathrm{CC}\ (\%) = \left(\frac{(180\times12)+(110\times12)}{3600}\right) \times 100 = 96.6\%$

Adding the 5th train, $\mathrm{CC}\ (\%) = \left(\frac{(180\times13)+(110\times12)}{3600}\right) \times 100 = \mathbf{101.6\% > 100\%}$

Thus, available capacity in section B1 is 4 trains. It means that maximum 24 trains per hour can operate along the section B1.



(a) Before compression



(b) After compression

Figure 5.8 Headway time between trains in the section B1 (a) before compression (b) after compression

5.3.4 Capacity Utilisation

Four aspects for measuring capacity utilization including number of trains (**Section 3.3.2.1**), velocity deviation (**Section 3.3.2.2**), timetable heterogeneity (**Section 3.3.2.3**), and punctuality in terms of travel time (**Section 3.3.2.4**) are determined.

5.3.4.1 Number of trains

The maximum number of trains is calculated by **Equation (3-26)**. In this test case, assuming that two successive trains are coupled into the same convoy. The first train in each convoy operates under the MBS. Thus, the maximum number of trains in each section can be calculated by **Equation (5-1)**.

$$C^{max} = \frac{3600}{\left(\Delta t_{k}^{vcs} + \Delta t_{k+N}^{MBS}\right)/N} \tag{5-1}$$

Where Δt_{k}^{vcs} and Δt_{k+N}^{MBS} refer to headway time between trains in the same convoy and the headway time between the last and the first train in successive convoy respectively and N is the number of trains built into the same convoy.

5.3.4.2 Velocity deviation

The rate of velocity deviation of trains within the defined time period is calculated by **Equation (3-26)**.

5.3.4.3 Heterogeneity

The rate of timetable heterogeneity (HET) within the defined time period is calculated by **Equation (3-37)**.

5.3.4.4 Travel time

Travel time refers to the time that a train has operated from station A to the terminal station B. In this part, the arrival times of both leading train 1 and following train 2 are simulated and compared among the compared cases. It is noted that other trains in the convoys behind results the same travel time because they have travelled using the same operational parameters without secondary delay.

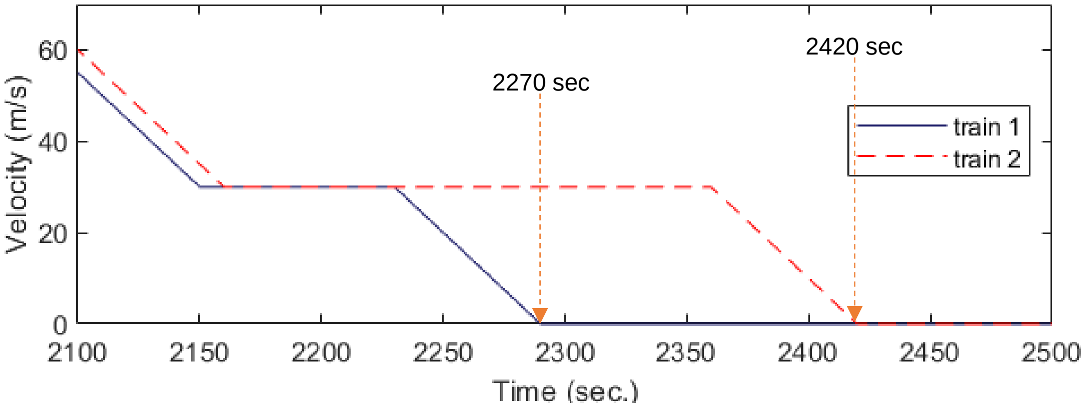


Figure 5.9 Simulated arrival times

5.4 Test cases and simulation results

The following train's movement of different values of 16 parameter shown in **Table 5.2** are simulated based on the proposed state movement in **Section 3.2.1**.

Table 5.2 Parameters affecting route capacity

Parameters	Variable	Cases
1. Number of trains	N	(a) 2 trains (b) 3 trains (c) 4 trains (d) 5 trains
2. Route length	z^{total}	(a) 100 km (b) 125 km (c) 150 km (d) 175 km
3. Maximum braking rate	b^{max}	(a) 0.3 m/s^2 (b) 0.4 m/s^2 (c) 0.5 m/s^2 (d) 0.6 m/s^2
4. Operational braking rate	b	(a) 0.2 m/s^2 (b) 0.3 m/s^2 (c) 0.4 m/s^2 (d) 0.5 m/s^2
5. Merging velocity gap	Δv_k^{mer}	(a) 5 m/s (b) 10 m/s (c) 15 m/s (d) 20 m/s
6. Merging velocity	v_k^{mer}	(a) 40 m/s vs. 45 m/s (b) 45 m/s vs. 50 m/s (c) 50 m/s vs. 55 m/s (d) 55 m/s vs. 60 m/s
7. Operating velocity	v^{opt}	(a) 45 m/s (b) 50 m/s (c) 55 m/s (d) 60 m/s
8. Splitting velocity gap	Δv_k^{spt}	(a) 4 m/s (b) 5 m/s (c) 6 m/s (d) 7 m/s
9. Splitting velocity	v_k^{spt}	(a) 45 m/s vs. 40 m/s (b) 50 m/s vs. 45 m/s (c) 55 m/s vs. 50 m/s (d) 60 m/s vs. 55 m/s
10. Junction velocity limit	v^{maxp}	(a) 20 m/s (b) 25 m/s (c) 30 m/s (d) 35 m/s
11. Diverging junction’s position	x^{dvr}	(a) 2 km (b) 3 km (c) 4 km (d) 5 km
12. Converging junction’s position	x^{cvr}	(a) 40 km (b) 50 km (c) 60 km (d) 70 km
13. Train length	l_k	a) 100 m b) 150 m c) 200 m d) 250 m

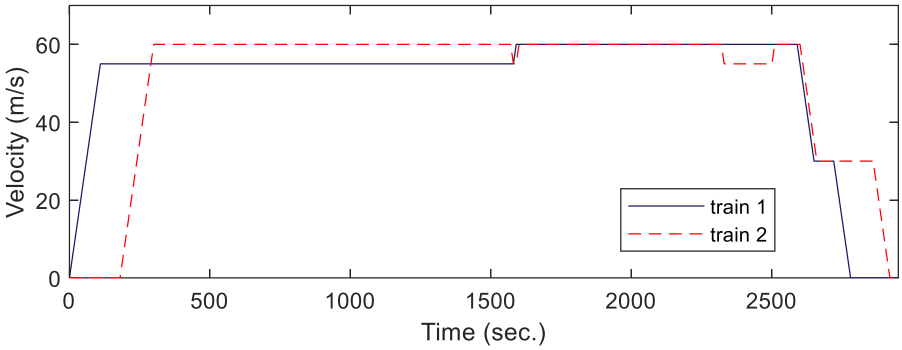
Table 5.2 Parameters affecting route capacity (Cont.)

Parameters	Variable	Cases
14. Safety margin	SM	(a) 2000 m (b) 2200 m (c) 2400 m (d) 2600 m
15. Turnout operation time	T^{pnt}	(a) 10 sec (b) 12 sec (c) 14 sec (d) 16 sec
16. Dispatching time	ΔH_k	(a) 180 sec (b) 210 sec (c) 240 sec (d) 270 sec

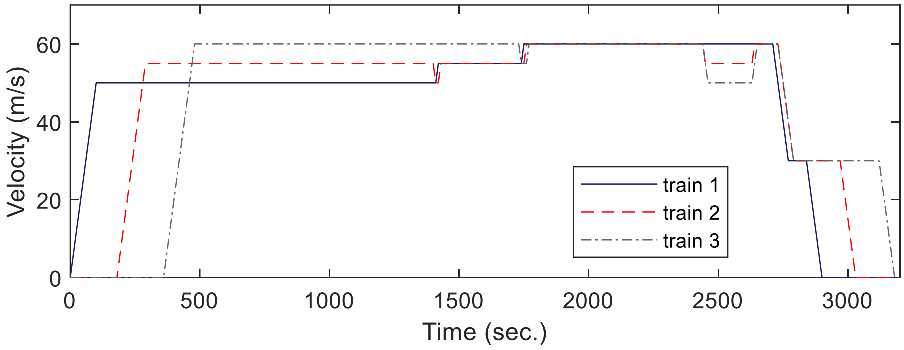
5.4.1 Number of trains built into the same convoy

It is assumed that there are different number of trains, in which 2 trains, 3 trains, 4 trains, or 5 trains are built into the same convoy. The successive trains have been merged and split out with 5 m/s velocity difference. The velocity profiles of all compared cases are shown in **Figure 5.10**. It is obviously seen that building a lower number of trains into the same convoy uses a shorter distance to transfer trains into the convoy state.

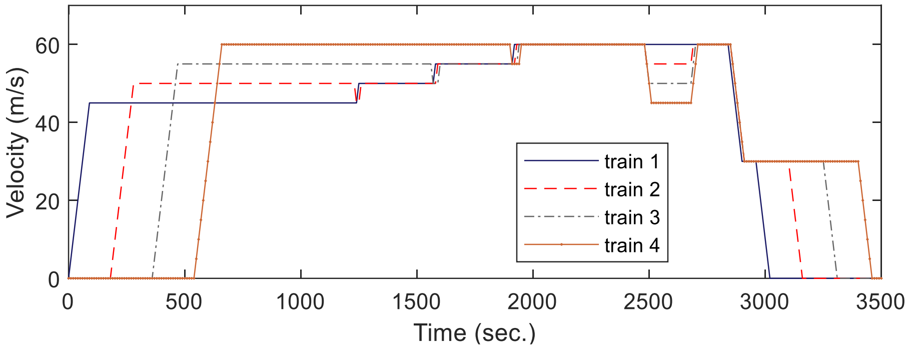
The capacity consumption and the maximum number of trains in each section are shown in **Table 5.3**. It is found that the percentage of capacity consumption in all sections is significantly decreased with the increase of the number of trains built as the same convoy. Especially in the section B1, the capacity consumption is obviously different. This is because the headway time between successive trains in the same convoy measured at the end of this section is severely decreased compared to the headway time at the beginning of the section. If only 2 trains are built into the same convoy, only 19% unused capacity will be available, in which only 4 additional trains could be inserted into the section. Interestingly, if we build 5 trains into the same convoy, approximately 47% of route capacity is unused allowing 18 trains inserted into the section.



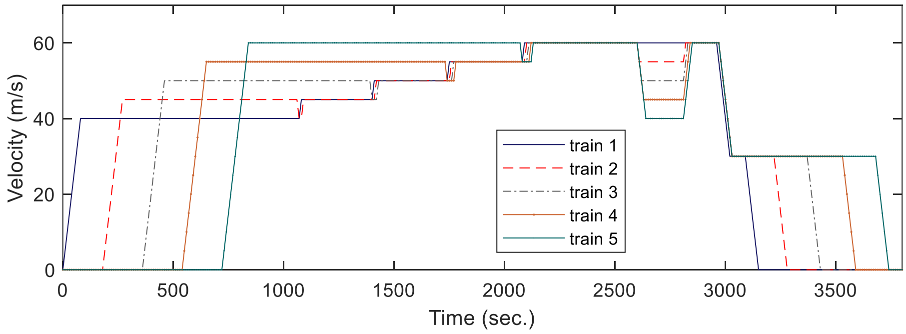
(a) 2 trains



(b) 3 trains



(c) 4 trains



(d) 5 trains

Figure 5.10 Velocity profiles of different number of trains in the same convoy

At the end of section B2, the headway time between in the same convoy must be extended to at least 130 sec (the minimum headway time required for passing through the diverging junction). The simulated result shows that building more trains into the same convoy will result a higher unused capacity. However, the rate of capacity consumption in each case is not obviously different due to the increase in headway time when trains pass the junction.

Table 5.3 Capacity consumption of different number of trains in a convoy

No. of trains in the same convoy	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
2	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
3	68.9	68.3	73.9	28 (28.4)	27 (27.7)	27 (27.0)
4	59.7	65.0	73.6	33 (33.5)	26 (26.7)	27 (27.7)
5	52.2	62.5	69.4	38 (38.3)	26 (26.9)	27 (27.3)

The velocity deviation, HET, and travel time of train 1 and 2 in each case are calculated as presented in **Table 5.4**. Building more trains will force the front trains operating by low velocity than their optimal velocity for a longer distance. Thus, the rate of velocity deviation is increased with the increase of the number of trains in the same convoy. As the front trains have operated by a lower velocity, their travel time is also increased. Building more trains into the same convoy makes the timetable more complicated when approaching the diverging junction. This is because the trains need to split out from the convoy in order to stop at different platforms. The rate of HET tends to be increased with the increase of the number of trains in the same convoy. Three aspects including velocity deviation, HET, and travel time could not be used to explain how the number of trains in the same convoy affect route capacity because the train 1 and train 2 in each case have operated by different merging velocity.

Table 5.4 Capacity utilization of different number of trains in a convoy

No. of trains in the same convoy	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
2	1.55	0.43	2760	2720
3	4.04	0.47	2900	2860
4	6.36	0.48	3000	2960
5	8.48	0.49	3130	3100

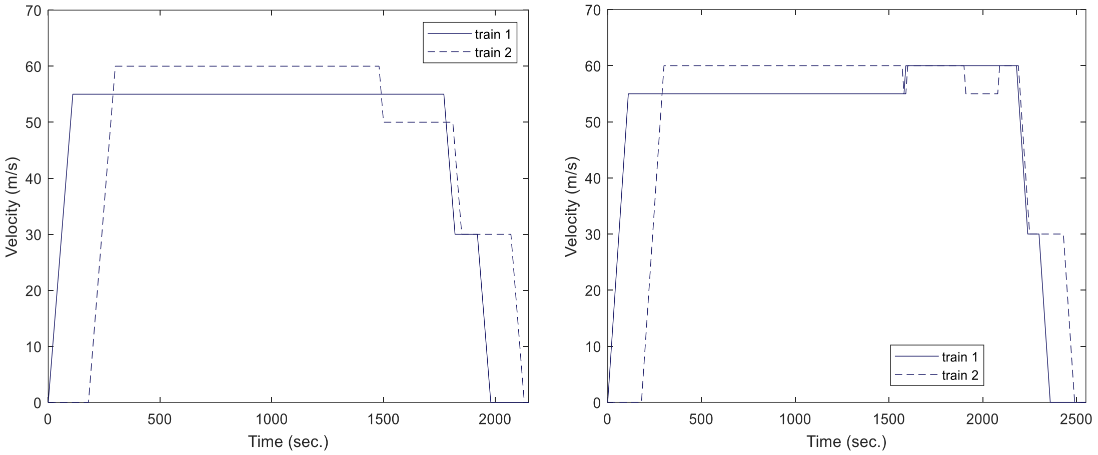
It could be concluded that the capacity consumption can be explained by the maximum number of trains that could operation within the section. Building a higher number of trains increases the headway time behind and/or in front of the convoy increasing unused capacity allowing a higher number of trains inserted into the section.

5.4.2 Route length

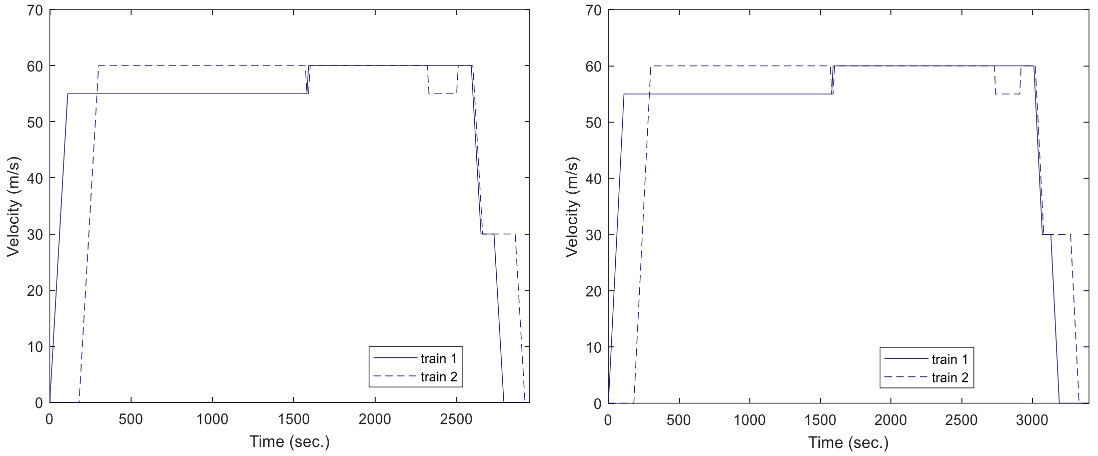
It is assumed that a train convoy including two trains has operated through the different route lengths ranged between 100 km – 175 km. The velocity profiles of a couple of trains proceeding along the different route length are shown in **Figure 5.11**. It is obviously seen that this parameter is related to the length of convoy zone (The zone that a couple of trains has operated under the convoy state). Because a couple of trains in all compared cases has been merged into the same convoy by using the same operational parameter, the merging distance or the distance covered for merged into the same convoy is the same. Thus, a longer route length increases the distance that the trains have proceeded under the convoy state.

In the first case, 100 km route length, two successive trains could not be transferred to the convoy state before reaching the splitting point. The headway time between them measured at the splitting point is higher than the headway time of the other three cases. As a result, the percentage of capacity consumption in the section B1 is lower than the other cases (**Table 5.5**). This is because the actual headway time between trains at the end of section B1 could be compressed more resulting a higher unused capacity. The rate of capacity consumption of all compared cases in the section B2 and C are the same at 72.2% and 75% respectively. The results are the same because of the same headway time between trains when a couple of trains has passed through the diverging junction and stopped at the station B.

For short route length, the trains are still in the merging state when they reach the splitting point. It means that a leading train has operated by its merging velocity which is normally lower than the optimal velocity before starting splitting. As a result, the rate of velocity deviation is much higher compared to the other cases (**Table 5.6**). However, the rate of HET results are in a different direction. The HET is lower than the other cases, due to a slight difference between the shortest and arrival headway time. The HET in other cases is not different because the shortest headway time and the headway time between trains when they pass through the diverging junction are equal.



(a) 100 km (b) 125 km



(c) 150 km (d) 175 km

Figure 5.11 Velocity profiles of different route lengths

Table 5.5 Capacity consumption of different route lengths

Route length (km)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
100	77.8	72.2	75.0	25 (25.7)	27 (27.7)	26 (26.7)
125	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
150	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
175	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

Table 5.6 Capacity utilization of different station spacings

Route length (km)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
100	2.96	0.38	1950	1930
125	1.84	0.43	2330	2290
150	1.55	0.43	2760	2720
175	1.34	0.43	3180	3140

*** Due to the different route length, the travel time is not compared.

In conclusion, the capacity consumption will change if a couple of trains can be transferred to the convoy state where the headway time between trains in the same convoy is minimized. Applying the VCS to control trains operating along the short distance will result a higher headway time, thus allowing insertion of more trains into the same route.

5.4.3 Maximum braking rate

Two successive trains have been built into the same convoy and split out by using 5 m/s velocity difference. In this test, it is assumed that the maximum braking rate of the leading train (the first train) in all convoys is 5 m/s^2 but the braking rate of the following train is different ranged between 0.2 m/s^2 – 0.5 m/s^2. Referring to **Equation (3-10)**, the maximum braking rate that a following train can apply directly relates to the minimum headway time between trains. A lower maximum braking rate requires a longer distance to stop increasing the headway time away from a leading train.

Figure 5.12 shows the relationship between the maximum braking rate and the minimum headway time between trains under the VCS. It is seen that the minimum headway time is increased with the decrease of the maximum braking rate. It also impacts on the dispatching headway time in which a lower braking rate allows a lower number of trains departing from the station.

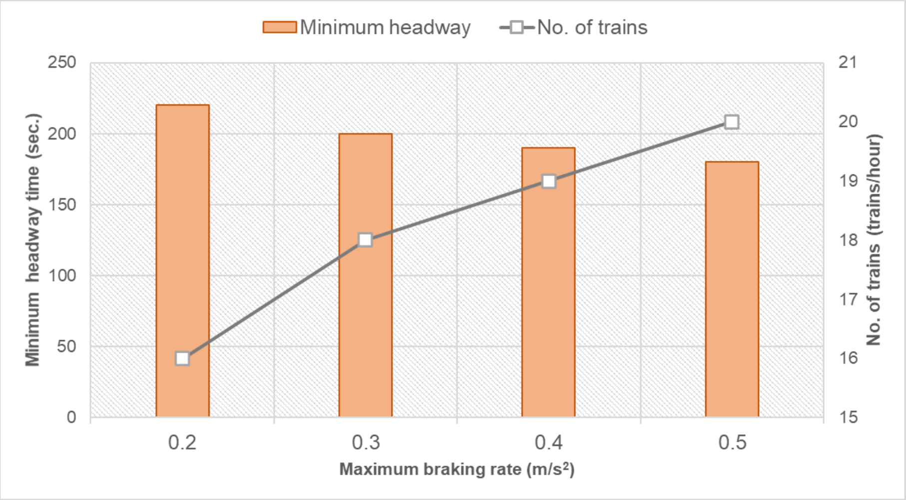
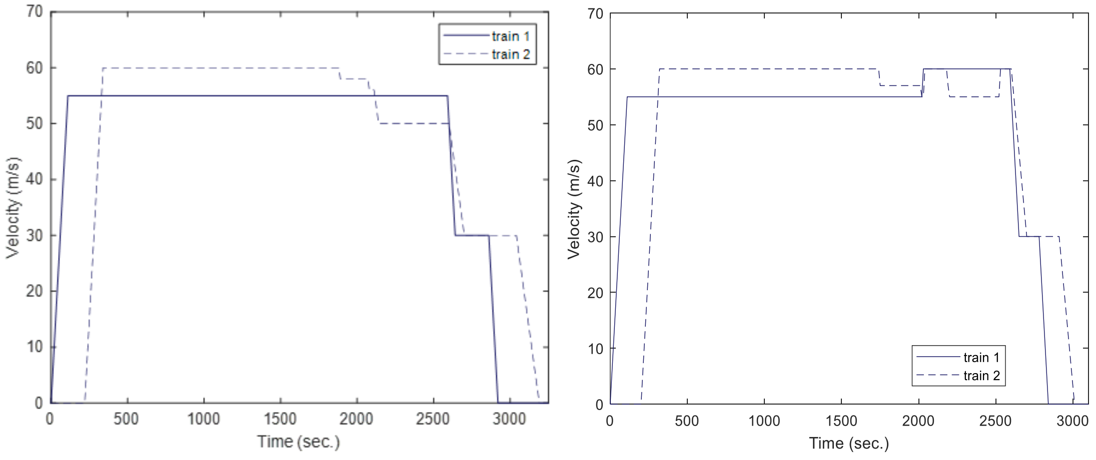
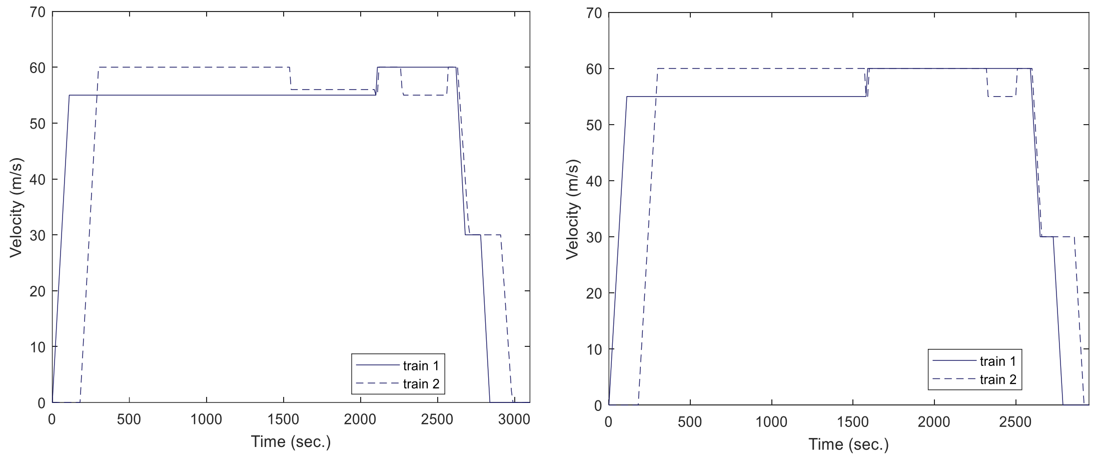


Figure 5.12 Relationship between maximum braking rate and the minimum headway time.

The simulated velocity profiles of trains with different maximum braking rates are shown in **Figure 5.13**. It is assumed that a following train in all cases starts splitting at the same point. It is obviously seen that the headway time between trains in the case of 0.2 m/s^2 maximum braking rate could not be extended to the minimum headway time. In the section B1, the capacity consumption of all cases is pretty much the same but the number of trains that could operate within the section is different. A higher maximum braking rate results a higher number of trains that could operate in the same section.



(a) 0.2 m/s^2 (b) 0.3 m/s^2



(c) 0.4 m/s^2 (d) 0.5 m/s^2

Figure 5.13 Velocity profiles of different maximum braking rates

In the section B2 and C, it is obviously seen that the percentage of capacity consumption is decreased with the increase of the maximum braking rate. As a result, the percentage of unused capacity is higher allowing a higher number of trains to be inserted into the sections.

Table 5.7 Capacity consumption of different maximum braking rates

Max. braking rate (m/s^2)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
0.2	80.0	80.0	100.0	20 (20.0)	20 (20.0)	16 (16.0)
0.3	82.5	75.0	80.0	21 (21.8)	24 (24.0)	22 (22.5)
0.4	80.8	74.2	76.4	23 (23.2)	24 (24.8)	24 (24.8)
0.5	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

The percentage of capacity consumption also relates to the rate of velocity deviation, HET, and travel time. The percentage of capacity consumption is decreased providing a higher rate of unused capacity relating to the decrease of velocity deviation, HET, and travel time. For a lower maximum braking rate, the rate of velocity deviation is increased because a couple of trains needs a longer distance to be coupled and transferred to the convoy state. Consequently, both trains use a longer time to operate from station A to B. In addition, the headway time when passing the junction is higher. As a result, the rate of HET is increased.

Table 5.8 Capacity utilization of different maximum braking rates

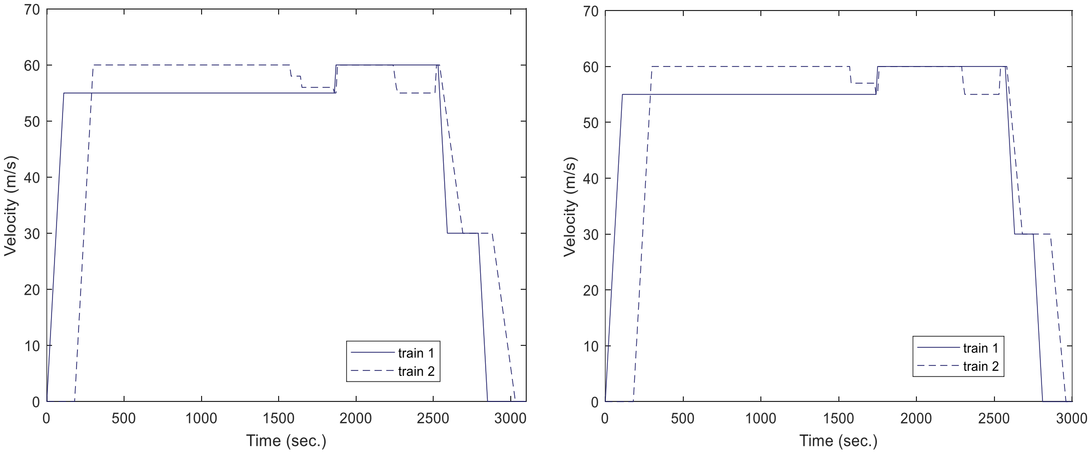
Maximum braking rate (m/s^2)	Velocity deviation (m/s.)	HET	Travel time (sec)	
			Leading train	Following train
0.2	3.00	0.47	2920	2970
0.3	1.87	0.49	2840	2810
0.4	2.43	0.45	2890	2860
0.5	1.55	0.43	2760	2720

In conclusion, the capacity consumption is decreased with the increase of maximum braking rate. Using a higher maximum braking rate requires a shorter distance to stop that could help a couple of trains to be transferred to the convoy state earlier. As a result, the trains could operate by their optimal velocity for a longer time, reducing travel time and rate of velocity deviation.

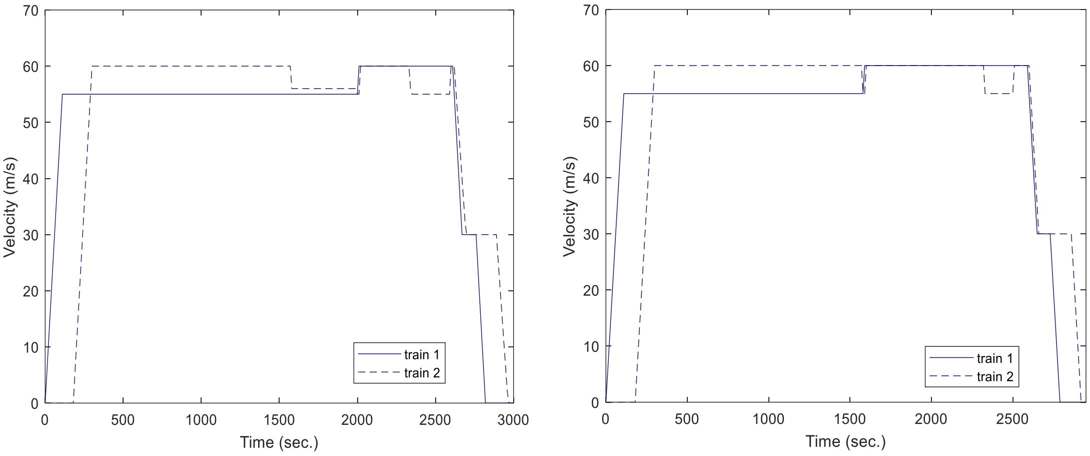
5.4.4 Operating braking rate

Assuming that a couple of trains in the same convoy have the same maximum braking rate at 0.5 m/s^2 but the following train will brake by using different braking rates ranging between 0.2 m/s^2 and 0.5 m/s^2. The minimum safe distance between trains required for each case is equal because it is calculated from the maximum braking rate at 0.5 m/s^2.

The velocity profiles of a couple of trains in four different cases are shown in **Figure 5.14**. It is obviously seen that a couple of trains uses a shorter distance for merged into the same convoy when the following train applies a higher braking rate to be transferred into the convoy state. This is due to the condition restricted in the proposed state movement (**Figure 3.8**), in that the following train is stimulated to decelerate to the same velocity as its front train when the distance separated from the front train is equal or shorter than the minimum safe distance. If the following train applies a lower braking rate, its velocity is still higher than the leading train’s velocity. Then, it could operate by constant velocity for a while as the decrease of minimum safe distance. It operates by constant velocity until the distance separated from the leading train is shorter than minimum safe distance that will force the following train to decelerate again.



(a) 0.2 m/s^2 (b) 0.3 m/s^2



(c) 0.4 m/s^2 (d) 0.5 m/s^2

Figure 5.14 Velocity profiles of different braking rates

According to the percentage of capacity consumption shown in **Table 5.9**, it is seen that the percentage of capacity consumption in the section C is different. It is decreased with the increased of operating braking rate. Additional four trains could be inserted into the section C when a following train decelerates by 0.2 m/s^2. Six extra trains could be inserted into the section if a following train decelerates by 0.5 m/s^2. The percentage of capacity consumption in the section B1 and B2 is equal because the successive trains have been merged into the same convoy by using the same merging pattern resulting the same headway time when trains have passed through the converging junction and splitting point. As a result, additional 4 trains and 7 trains can be inserted into the section B1 and B2 respectively.

Table 5.9 Capacity consumption of different operating braking rates

Operating braking rate (m/s²)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
0.2	80.6	72.2	83.3	24 (24.8)	27 (27.7)	24 (24.0)
0.3	80.6	72.2	80.6	24 (24.8)	27 (27.7)	24 (24.8)
0.4	80.6	72.2	77.8	24 (24.8)	27 (27.7)	25 (25.7)
0.5	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

Another reason that increases the percentage of capacity consumption is the velocity deviation rate (**Table 5.10**). The velocity deviation rate is reduced if a train could operate by its optimal velocity covering a longer distance. It is found that using a higher braking rate could help a couple of trains to be transferred to the convoy state earlier reducing the rate of velocity deviation. As the trains have operated by optimal velocity for a longer time, their travel times tend to be decreased allowing more trains passing the same point.

The minimum headway time required for passing through the diverging junction is equal. However, the simulated headway time between trains measured at the junction is different. In the case that the following breaks by using a lower braking rate than the braking rate applied by its leading train, the headway time between them has been decreased and might be lower than the minimum headway time causing unsafe situation. In this test, if the following train brakes by 0.2 m/s^2 and 0.3 m/s^2, the headway time separated from the leading train is lower than the minimum safe headway. Thus, both 0.2 m/s^2 and 0.3 m/s^2 cannot show the relationship between capacity consumption and utilisation.

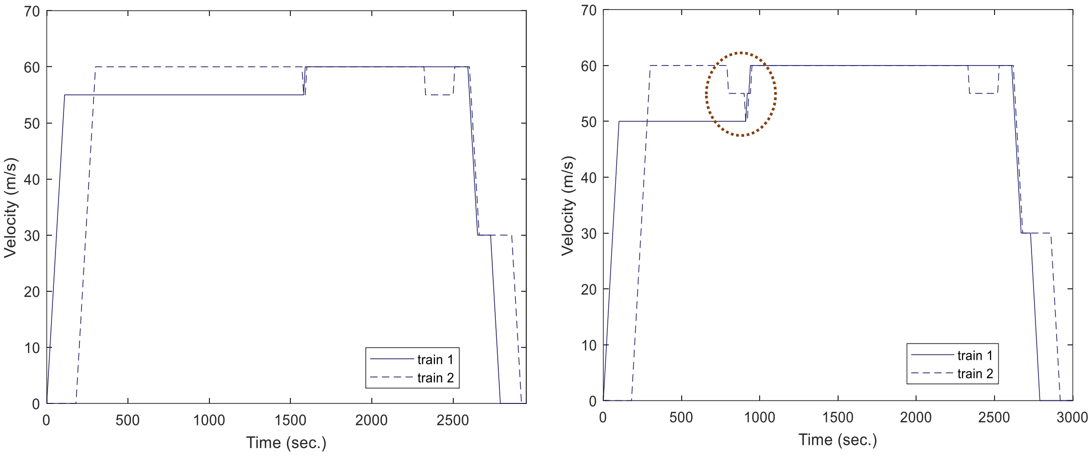
Table 5.10 Capacity utilization of different braking rates

Operating braking rate (m/s²)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
0.2	2.22	0.27	2850	2800
0.3	1.70	0.39	2810	2790
0.4	2.27	0.44	2820	2790
0.5	1.55	0.43	2760	2720

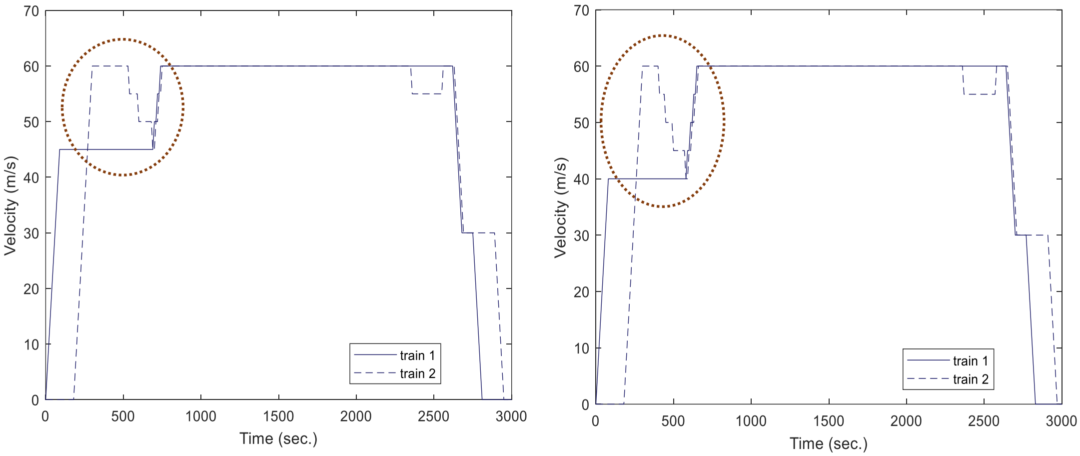
Focusing on the case that the following train breaks by 0.4 m/s^2 and 0.5 m/s^2, the rate of velocity deviation, HET, and travel time are decreased with the increased of operating braking rate. Thus, using a higher braking rate could decrease the rate of capacity consumption allowing more trains to insert into the same section. Braking by using a higher rate will force a couple of trains to be transferred into the convoy state earlier reducing the rate of velocity deviation and travel time. It is noted that this parameter only impacts on the section which force a train to decelerate such as the section which has a diverging junction or station.

5.4.5 Merging velocity difference

Assuming that a couple of trains has been merged into the same convoy by using different merging velocity difference ranged between 5 – 20 m/s.



(a) 5 m/s (b) 10 m/s



(c) 15 m/s (d) 20 m/s

Figure 5.15 Velocity profiles of different merging velocity gaps

Figure 5.15 shows the velocity profiles of a couple of trains when the trains have been merged into the same convoy by using different merging velocity difference. It is obviously seen that the merging velocity difference relates to the total time that the following train catches up with the leading train. Building a convoy by using a higher velocity difference requires a lower time or a shorter distance to transfer a couple of trains into the convoy state. According to the percentage of capacity consumptions shown in **Table 5.11**, it is seen that only the capacity consumption in the section B1 is different. The rate of capacity consumption in this section is about 81% when building a convoy by 5 m/s velocity difference. It is reduced to 66.7% when a couple of trains has been merged into the same convoy by using a higher velocity difference ($\Delta v_k^{mer} \geq 10$ m/s). This is because the successive trains in the case of higher velocity difference can be transferred to the convoy state before passing the converging junction. Consequently, the headway time between trains measured at the end of this section is equal resulting the same rate of capacity consumption. Only four extra trains could be inserted into the section when building a convoy by 5 m/s velocity difference. But, when a couple of trains has been built by $\Delta v_k^{mer} \geq 10$ m/s, 10 additional trains could be inserted.

Table 5.11 Capacity consumption of different merging velocity gaps

Merging velocity gap (m/s)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
5	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
10	66.7	72.2	75.0	30 (30.0)	27 (27.7)	26 (26.7)
15	66.7	72.2	75.0	30 (30.0)	27 (27.7)	26 (26.7)
20	66.7	72.2	75.0	30 (30.0)	27 (27.7)	26 (26.7)

Three aspects of capacity utilisation: velocity deviation, HET, and travel time does not relate to the rate of capacity consumption. They could not be used to analyse how the section capacity is utilised. Generally, the percentage of capacity consumption is theoretically increased with the increase of velocity deviation rate, timetable HET, and/or travel time. However, the capacity consumption of this parameter is increased although the velocity deviation rate and travel time is decreased. The HET of all cases results in the same rate at 0.43 due to the same headway times when passing through the splitting point and the diverging junction.

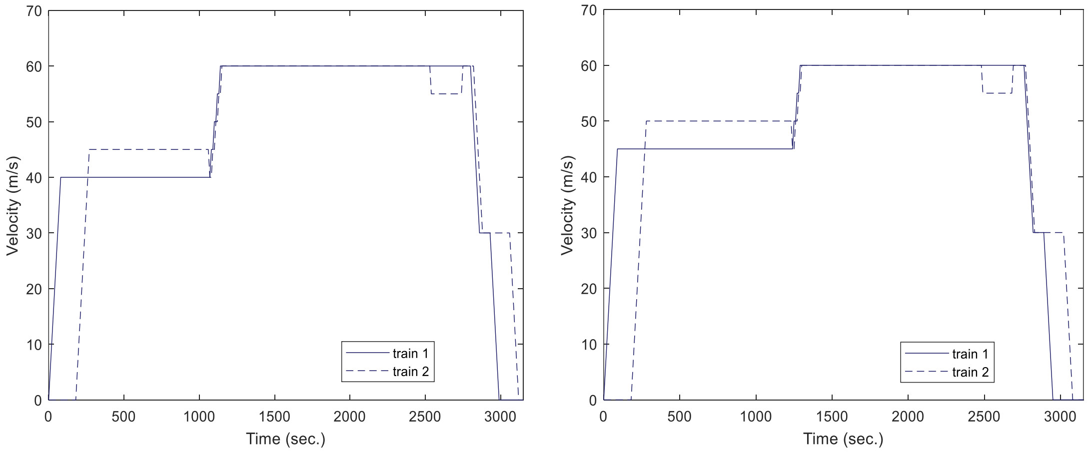
Table 5.12 Capacity utilization of different merging velocity gaps

Merging velocity gap (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
5	1.55	0.43	2760	2720
10	1.83	0.43	2770	2730
15	1.93	0.43	2780	2740
20	2.58	0.43	2810	2770

In conclusion, using a lower merging velocity difference may result a lower percentage of capacity consumption due to a higher headway time between trains measured at the same point. Interestingly, the capacity consumption will be the same if the successive trains could be transferred to the convoy state before reaching the end of the defined section.

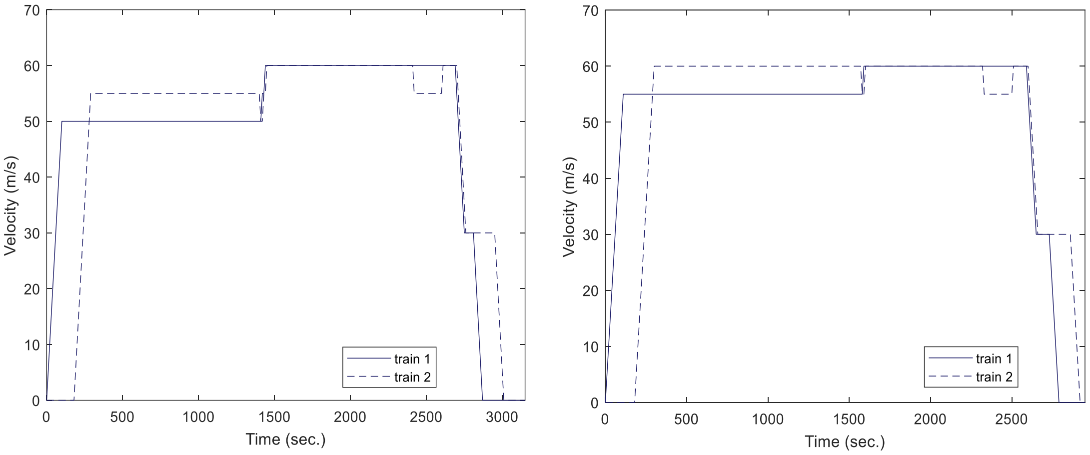
5.4.6 Merging velocity

Assume that two successive trains have been built into the same convoy by using 5 m/s merging velocity difference. However, the operating velocity used for merged into a convoy is different as shown in **Figure 5.16**. It is seen that building a convoy by using a lower velocity could help the trains to be transferred to the convoy state earlier increasing the distance that trains have proceed in the convoy state. The merging velocity relates to the minimum safe distance required when trains have operated under the VCS (**Equation (3-10)**). Because a lower merging velocity requires a shorter minimum safe distance, the separation distance between trains measured at the splitting point (end of zone B1) is lower reducing the percentage of capacity consumption of the section B1. As a result, a higher number of trains could be inserted into the section B1.



(a) 40 m/s vs. 45 m/s

(b) 45 m/s vs. 50 m/s



(c) 50 m/s vs. 55 m/s

(d) 55 m/s vs. 60 m/s

Figure 5.16 Velocity profiles of different merging velocities

As seen in **Table 5.13**, when the leading and the following have proceeded by 40 m/s and 45 m/s for merged into the same convoy, 11 additional trains could be inserted into the section B1. However, only four extra trains could be added if the trains have been merged by 55 m/s and 60 m/s. As the trains in all cases use the same pattern for splitting, the headway time when passing through the diverging junction and stopping at the station B is not different resulting the same rate of capacity consumption in both section B2 and C.

Table 5.13 Capacity consumption of different merging velocities

Merging velocity (m/s)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
40 vs. 45	63.9	72.2	75.0	31 (31.3)	27 (27.7)	26 (26.7)
45 vs. 50	66.7	72.2	75.0	30 (30.0)	27 (27.7)	26 (26.7)
50 vs. 55	75.0	72.2	75.0	26 (26.7)	27 (27.7)	26 (26.7)
55 vs. 60	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

It is in contrast to the assumption that the capacity consumption is increased with the rise of velocity deviation rate. Using a lower merging velocity results a lower percentage of capacity consumption although the rate of velocity deviation is high. It is similar to the trend of travel time that is increased because the trains have been merged by using a lower velocity. The HET of all cases is similar due to the same headway times measured at splitting point and the diverging junction. Thus, it can be said that the rate of velocity deviation, HET, and travel time do not relate to the percentage of capacity consumption.

Table 5.14 Capacity utilization of different merging velocities

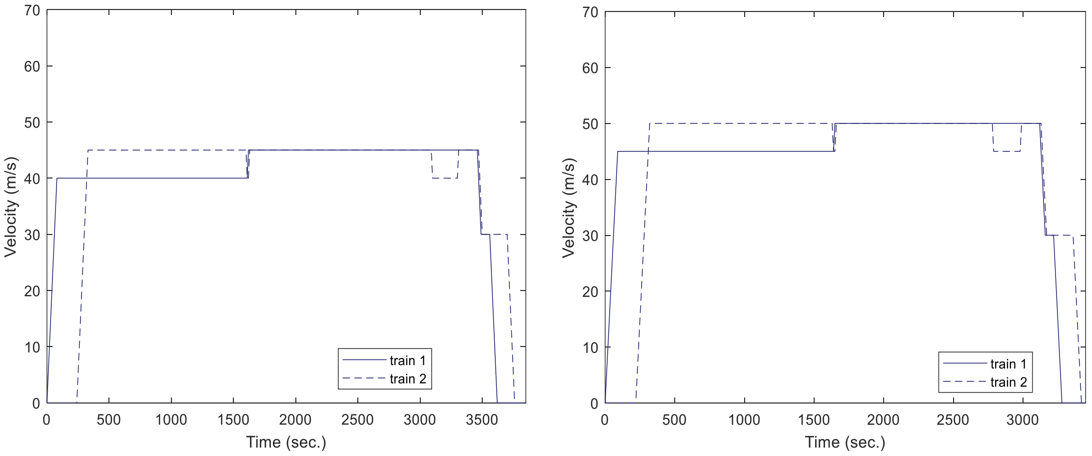
Merging velocity (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
40 vs. 45	5.73	0.43	2980	2940
45 vs. 50	4.91	0.43	2930	2890
50 vs. 55	3.55	0.43	2850	2810
55 vs. 60	1.55	0.43	2760	2720

To sum up, using a lower velocity for merged into the same convoy will increase the rate of capacity consumption. Thus, the percentage of unused capacity is increased allowing a higher number of trains inserted into the same route.

5.4.7 Operating velocity

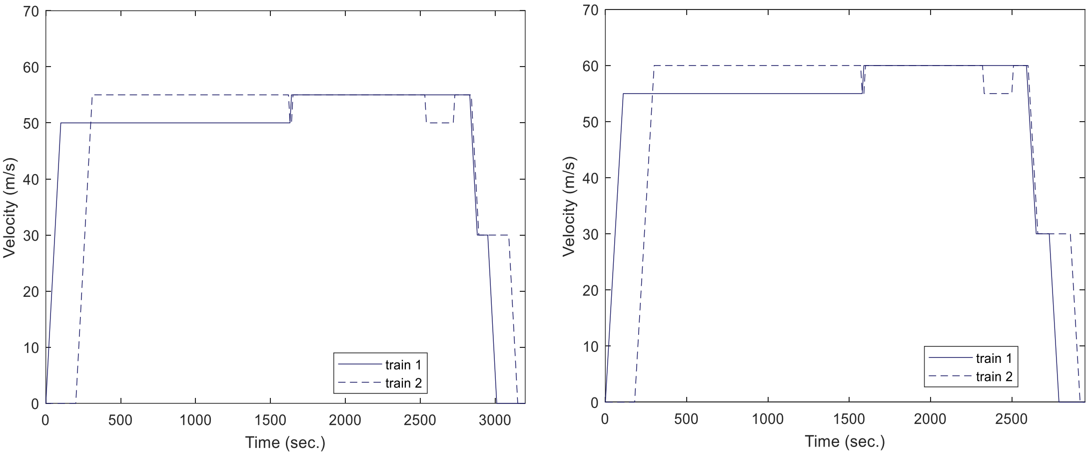
This parameter is determined based on the question that which train type (low or high-speed train) is more suitable to be controlled under the VCS. Assuming that a couple of trains in all cases are merged into the same convoy and split out from the convoy by using the same velocity difference at 5 m/s. However, they will operate by using different operating velocities ranged between 45 m/s and 60 m/s.

The simulated velocity profiles of different operating velocities are shown in **Figure 5.17**. It is found that using a lower operating velocity needs a shorter merging distance. As a result, the trains are transferred into the convoy state earlier. This is because the operating velocity directly impacts on the minimum safe distance between successive trains.



(a) 45 m/s.

(b) 50 m/s.



(c) 55 m/s.

(d) 60 m/s.

Figure 5.17 Velocity profiles of different operating velocities

The relationship between the operating velocity and the minimum headway time under the MBS is shown in **Figure 5.18**. It is obviously seen that the minimum headway time is increased with the decrease of the operating velocity. This is in contrast to the relationship between operating velocity and minimum safe distance under the VCS, in which the minimum safe distance is decreased with the decrease of operating velocity. The simulated results show that the minimum safe distance in four different operating velocity is slightly different. When we convert the term of minimum safe distance to the minimum headway time, it is found that using a higher operating velocity requires a lower headway time between trains. In this test, it is assumed that the trains depart from station A using the minimum headway time as the dispatching headway. Thus, the number of trains departing from station A is different as shown in **Figure 5.18**.

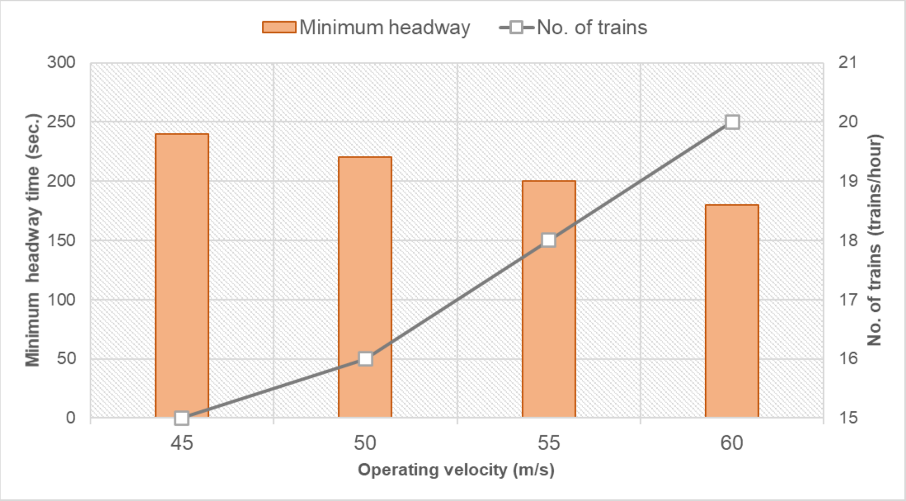


Figure 5.18 Relationship between operating velocity and the minimum headway time, and the number of trains departing from station A.

The percentage of capacity consumption and maximum number of trains in each section of different velocities are shown in **Table 5.15**. It is found that the percentage of capacity consumptions of all sections is increased with the increase of operating velocity. With 60 m/s operating velocity, 20 trains/hour at maximum can depart from station A allowing four additional trains inserted into the section B1. If the operating velocity is reduced to 45 m/s, five additional trains could be inserted. However, in case of 45 m/s operating velocity, only 15 trains/hour can depart from station A. Thus, the maximum number of trains with 60 m/s is 24 trains which is higher than the maximum number of trains if they proceed by 45 m/s.

In the section B2, approximately 11 trains could be inserted when trains proceed by 45 m/s and only seven trains could be added when they proceed by 60 m/s. In the section C, the maximum number of trains that could operate through the section are equal. This is due to the same minimum headway time required for passing through the diverging junction.

Table 5.15 Capacity consumption of different optimal velocities

Operating velocity (m/s)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
45	71.1	54.4	56.1	20 (20.6)	26 (26.7)	26 (26.7)
50	73.3	57.8	60.0	21 (21.8)	27 (27.7)	26 (26.7)
55	75.0	65.0	67.5	24 (24.0)	27 (27.7)	26 (26.7)
60	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

According to the capacity utilisation in **Table 5.16**, the rate of velocity deviation is decreased with the decrease of operating velocity due to a shorter distance that the trains need to be coupled as the same convoy. Because operating by a lower velocity requires a shorter time for merged into a convoy, a train will operate by its optimal velocity for a longer distance reducing rate of velocity deviation. In addition, operating by a lower velocity takes a longer travel time to proceed to the destination. This aspect contrasts with the theoretical relationship with the capacity consumption, in which the rate of capacity consumption is decrease with the decrease of travel time. It cannot be used to explain how the trains consume the route capacity. It is similar to the HET rate which could not be compered due to different departing headway time.

Table 5.16 Capacity utilization of different operating velocities

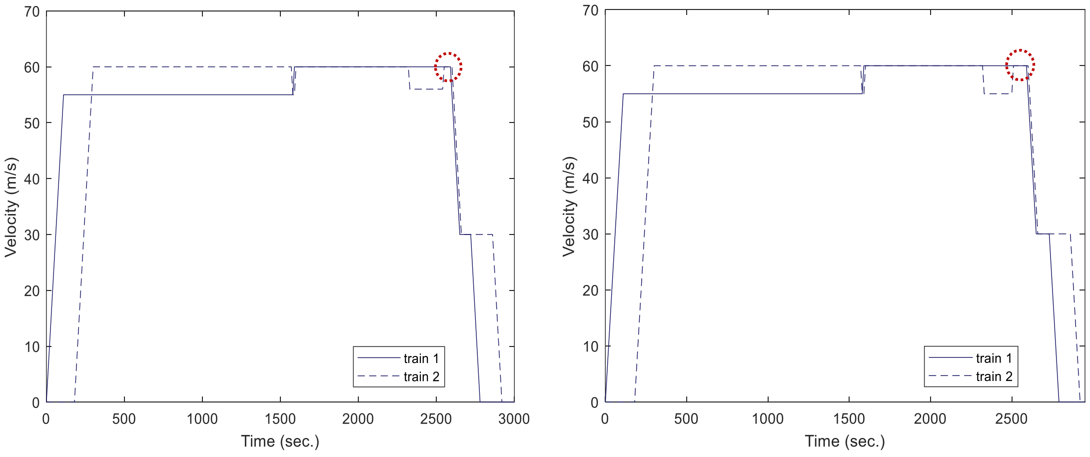
Operating velocity (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
45	0.90	0.42	3610	3520
50	1.07	0.45	3270	3180
55	1.30	0.45	2990	2930
60	1.55	0.43	2760	2720

In conclusion, this parameter directly impacts on the minimum headway time between trains. The headway time between trains when they are in the convoy state is increased with the increase of operating velocity. As a result, the percentage of capacity consumption is higher reducing the number of trains that can proceed on the same route.

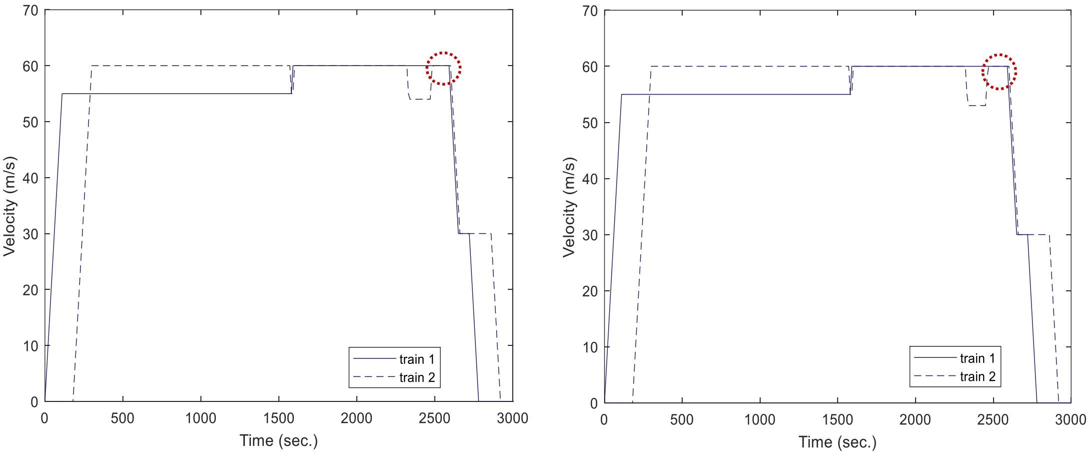
5.4.8 Splitting velocity difference

This parameter is determined based on the assumption that the splitting velocity difference relates to the distance that a following train has moved for splitting out from a convoy. It is assumed that two successive trains in all cases have been merged into the same convoy using the same velocity difference. However, they will split out from the convoy using different splitting velocity difference ranged from 4 – 7 m/s.

The simulated velocity profiles of trains when they have split out by different velocity difference are shown in **Figure 5.19**. It is seen that splitting out by using a lower splitting velocity difference needs a longer distance to split. Because the following train starts splitting at the same point, the distance between trains in all cases can be extended to minimum safe distance required at the junction. However, using a higher velocity difference to split out reduces the splitting distance forcing the following train to accelerate to the same velocity as the leading train earlier. The percentage of capacity consumption of different splitting velocity difference is shown in **Table 5.17**. It is seen that the percentage of capacity consumption in the section B1 and B2 is equal due to the same headway time between trains measured at the converging junction and splitting point.



(a) 4 m/s (b) 5 m/s



(c) 6 m/s (d) 7 m/s

Figure 5.19 Velocity profiles of different splitting velocity difference

Here we focus on the capacity consumption in the section C where a following train needs to decelerate for splitting out from the convoy, the minimum headway time required for passing the diverging junction of all cases is equal. Thus, the headway time between trains in all cases will be extended to 130 sec before passing the diverging junction. Thus, the headway time between trains measured at the diverging junction is equal at 130 sec resulting the same capacity consumption in the section C. Six extra trains could be inserted into the section C although the trains have split by using different velocity difference. It is noted that the capacity in this section is equal because the splitting distance is long enough allowing a following to split out. However, if the splitting distance is too short requiring high splitting velocity difference, the distance between trains might not be extended to the safe distance causing unsafe situation when passing through the junction.

Table 5.17 Capacity consumption of different splitting velocity difference

Splitting velocity difference (m/s)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
4	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
5	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
6	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
7	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

According to the rate of capacity utilisation shown in **Table 5.18**, the velocity deviation rates of all cases is slightly different due to a slightly different of the convoy distance after splitting (red dotted circle in **Figure 5.19**). The HET rate of all cases is equal due to the same shortest headway time and the headway time when passing through the diverging junction.

Table 5.18 Capacity utilization of different splitting velocity difference

Splitting velocity difference (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
4	1.56	0.43	2760	2730
5	1.55	0.43	2760	2720
6	1.54	0.43	2760	2720
7	1.53	0.43	2760	2720

It could be concluded that splitting by using the different velocity difference do not impact on capacity consumption. It does not impact on route capacity based on the condition that the splitting distance is long enough allowing the following train splitting out from the train convoy before passing a diverging junction.

5.4.9 Splitting velocity

Assuming that the trains in all cases have split by the same velocity difference at 5 m/s but the leading train will decelerate to different velocities including 45 m/s, 50 m/s, 55 m/s, and 60 m/s when reaching the splitting point. The minimum headway time required for passing through the diverging junction for all cases is 130 sec. However, due to different splitting velocity, the splitting distance or the total distance for extending the distance to the safe distance is different. The relationship between splitting velocity and optimal splitting distance is shown in **Figure 5.20** (The optimal splitting distance is estimated by using **Equation (3-23)**). It is seen that the optimal splitting distance is increased with the increase of splitting velocity.

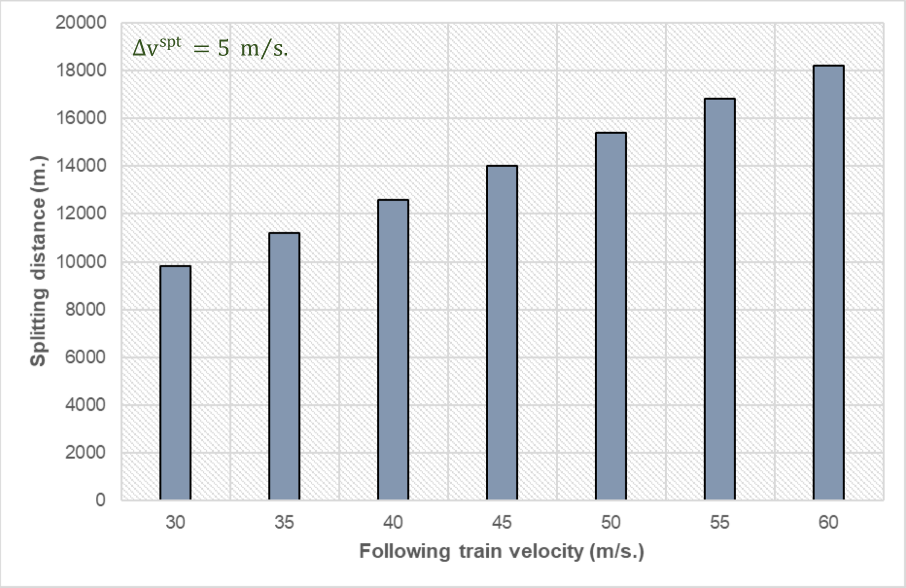
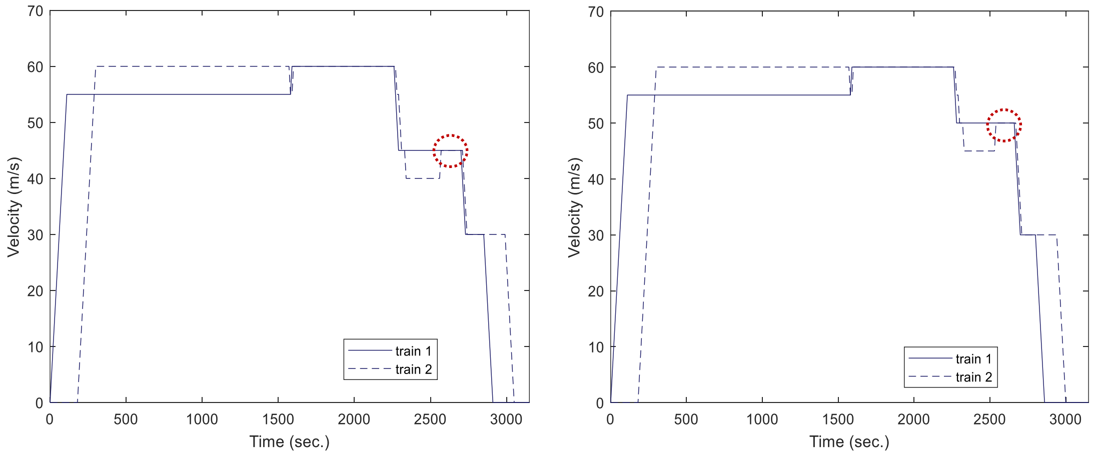


Figure 5.20 Relationship between splitting velocity and splitting distance

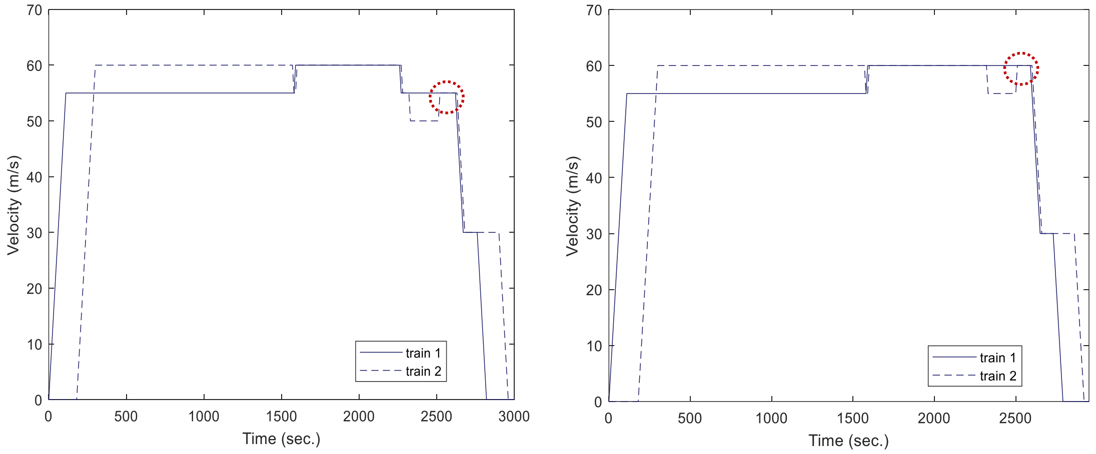
In this test, it is assumed that the following train in all cases starts splitting at the same point. The simulated velocity profiles of trains with different splitting velocities are shown in **Figure 5.21**. It is seen that splitting by using a lower velocity results a longer time that a couple of trains have platooned by the same velocity after splitting out (red dotted circle in **Figure 5.21**). This could be confirmed that splitting by using a lower velocity covers a shorter distance (or a shorter time) to extend the headway time between trains to the minimum safe headway required for passing through the junction.

According to the rates of capacity consumption shown in **Table 5.19**, it is seen that the percentage of capacity consumption of all cases in all sections are equal resulting the same maximum number of trains that could operate along the sections. This parameter may impact on capacity consumption in the section B1 and B2 if the route length is not long enough allowing a couple of trains transferred into the convoy state.



(a) 45 and 40 m/s

(b) 50 and 45 m/s



(c) 55 and 50 m/s

(d) 60 and 55 m/s

Figure 5.21 Velocity profiles of different splitting velocities

This parameter does not impact on the capacity consumption in the section C because the minimum headway time required for passing through the diverging junction is equal. Due to the same headway time between trains measured at splitting point and the diverging junction, the rate of HET in all cases is equal (**Table 5.20**). The rate of velocity deviation and travel time is increased with the decrease of splitting velocity because a couple of trains has split by velocity lower than its optimal velocity at 60 m/s.

Table 5.19 Capacity consumption of different splitting velocities

Splitting velocity (m/s)	**CC (%)**			**B1 (t/h)**	**B2 (t/h)**	**C (t/h)**
	B1	**B2**	**C**			
45 and 40	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
50 and 45	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
55 and 50	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
60 and 55	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

Table 5.20 Capacity utilization of different splitting velocities

Splitting velocity (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
45 and 40	3.64	0.43	2890	2850
50 and 45	2.87	0.43	2840	2800
55 and 50	2.16	0.43	2810	2770
60 and 55	1.55	0.43	2760	2720

To sum up, the splitting velocity does not impact on the capacity consumption if the splitting distance is long enough allowing a following train splitting out from the train convoy. Using a lower velocity for splitting from a convoy could help a couple of trains split out faster. It is suggested that, in the case of short station spacing, a couple of trains should split out from a convoy by using low splitting velocity.

5.4.10 Junction velocity limit

The junction velocity limit is the one parameter used to calculate the minimum safe distance required for passing the junction. It relates to the minimum safe distance in which a higher velocity limit requires a longer braking distance and needs a longer distance for splitting (See the equations to calculate the minimum safe distance in **Table 3.1**).

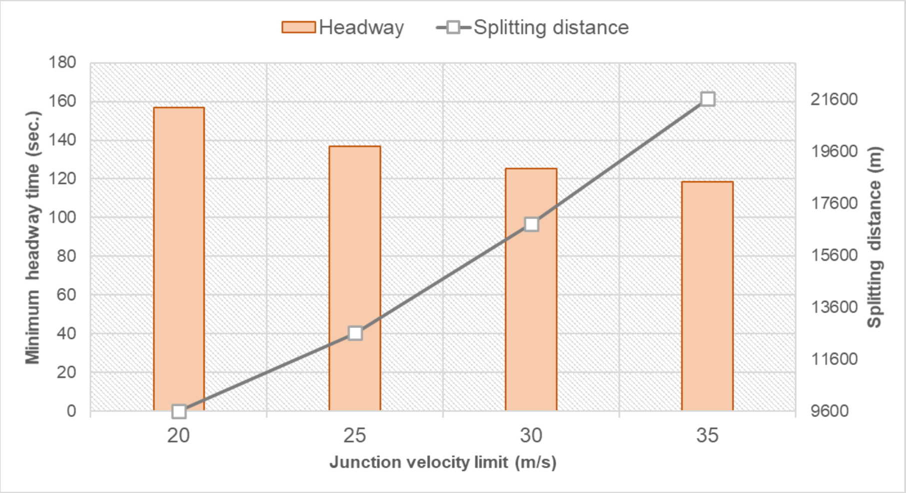
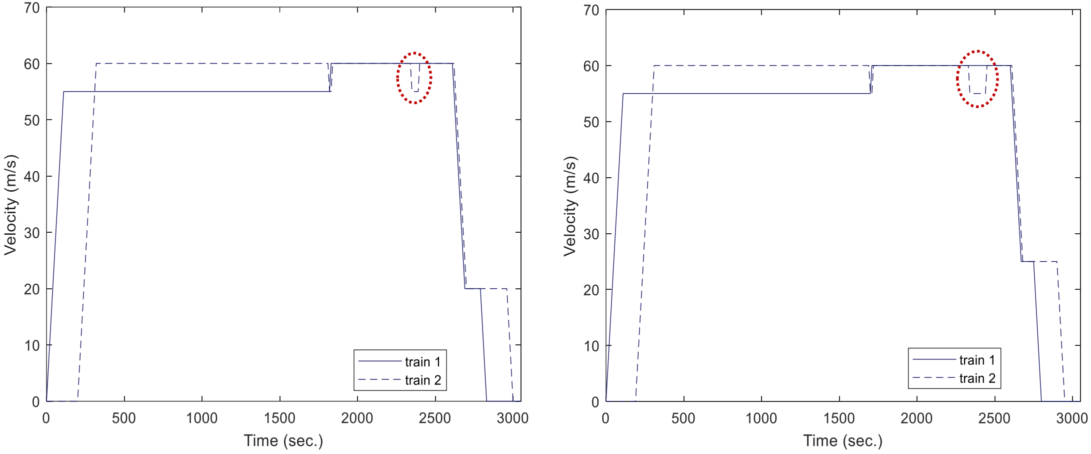


Figure 5.22 Relationship between junction velocity limit and minimum headway time and optimal splitting distance

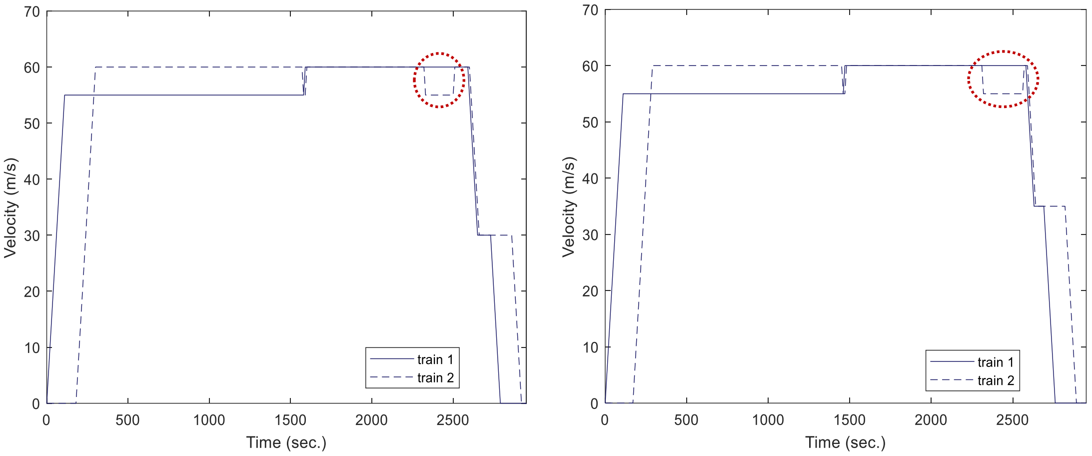
As seen in **Figure 5.22**, with 30 m/s junction velocity limit, at least 3760 m separation distance between trains is required. It is reduced to 3140 m when the velocity limit is reduced to 20 m/s. The minimum safe distance is converted to the minimum headway time to calculate maximum number of trains that could depart from the statin A in one hour time period. It is found that the minimum dispatching headway time for 20 m/s, 25 m/s, 30 m/s, and 35 m/s velocity limit is 200 sec, 190 sec, 180 sec, and 170 sec, respectively.

Thus, the maximum number of trains that could depart from the station A for 20 m/s, 25 m/s, 30 m/s, and 35 m/s velocity limit is 18, 19, 20, and 21 trains/hour respectively. **Figure 5.23** shows simulated velocity profiles of trains passing the junction with different junction velocity limits. It is seen that the splitting distance is increased with the increase of junction velocity limit.



(a) 20 m/s

(b) 25 m/s



(c) 30 m/s

(d) 35 m/s

Figure 5.23 Velocity profiles of different junction velocity limits

The percentage of capacity consumption of each section is shown in **Table 5.12**. The capacity consumption in the section B1 tends to be decreased with the increase of junction velocity limit due to different headway time when passing the converging junction. The maximum number of trains that can be inserted into the section is different although the trains have been built into the same convoy by the same operating velocity. Only three trains could be inserted into the section B1 if the junction velocity limit is 20 m/s. However, in the case of 35 m/s velocity limit, five trains could be inserted into the section.

The capacity consumption in both section B2 and C results the same trend in the section B1. The capacity consumption is decreased with the increase of junction velocity limit allowing a higher number of trains to operate along the section. This is because the minimum headway time required for passing through the junction is lower although the minimum safe distance is longer. With 20 m/s velocity limit, the minimum headway time between trains under the MBS is 200 sec allowing 18 trains departing from the station A. In this case, three, four, and three additional trains can be inserted into the section B1, B2, and C respectively. Compared to the case of 30 m/s velocity limit in which the minimum headway time is about 180 sec. 20 trains per hour will depart from the station A allowing four, seven, and six additional trains inserted into the section B1, B2, and C respectively.

Table 5.21 Capacity consumption of different junction velocity limits

Velocity limit (m/s)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
20	82.5	80.0	82.5	21 (21.8)	22 (22.5)	21 (21.8)
25	80.8	74.2	76.4	23 (23.2)	24 (24.8)	24 (24.8)
30	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
35	79.7	71.7	73.1	26 (26.7)	30 (30.0)	28 (28.8)

As a lower junction velocity limit requires a shorter minimum safe distance, a following train will cover a shorter distance (or a shorter time) to split out reducing the rate of velocity deviation. It is in contrast to the assumption that the percentage of capacity consumption is decreased with the decrease of velocity deviation. In this case, the rate of velocity deviation of the trains does not relate to the percentage of capacity consumption. Because the trains need a higher headway time for passing through the junction, the HET is increased as the decrease of junction velocity limit. The travel time could be used to explain how the trains consume the route. Passing the junction by a lower velocity normally takes a longer time to arrive at the destination. As a result, the number of trains that will arrive at the next station is lower.

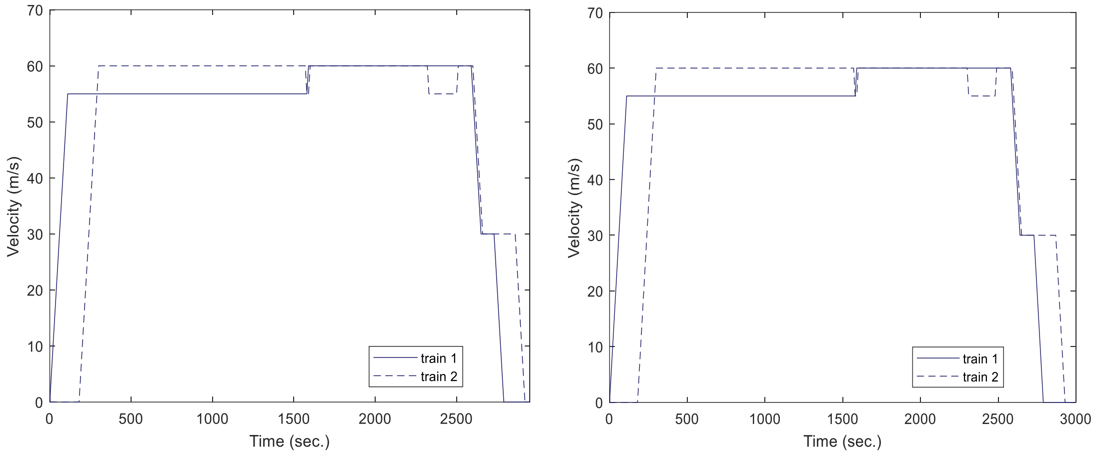
Table 5.22 Capacity utilization of different junction velocity limits

Junction velocity limit (m/s)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
20	1.42	0.49	2820	2790
25	1.48	0.45	2790	2760
30	1.55	0.43	2760	2720
35	1.62	0.38	2740	2700

To sum up, the junction velocity limit directly relates to the minimum headway time required for passing a junction. Passing a junction by using a higher velocity results a lower capacity consumption allowing a higher number of trains operating on the same route.

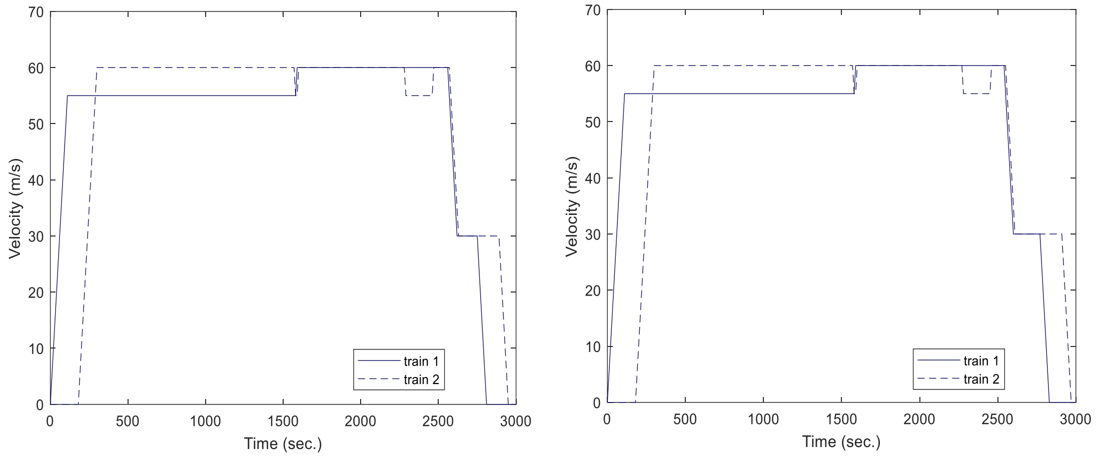
5.4.11 Diverging junction position

The aim of this test is to determine whether and how the position of a diverging junction impacts on the route capacity. The velocity profiles of trains when passing the diverging junction placed at different position at 2 km, 3 km, 4 km, and 5 km away from the next station are shown in **Figure 5.24**. It is seen that the velocity profiles of four compared cases are pretty the same.



(a) 2 km

(b) 3 km



(c) 4 km

(d) 5 km

Figure 5.24 Velocity profiles of different diverging junction's positions

According to the simulated results shown in **Table 5.23**, the capacity consumption in each section is the same due to the same headway time measured at the end of each section. As a result, the number of trains that could operate in each section, velocity deviation rate and HET are also the same. The travel time is slightly different and tends to be increased with the increase of the distance between the diverging junction and the next station.

This is because a longer distance between the diverging junction and station will force the trains to operate by a lower velocity over a longer distance.

Table 5.23 Capacity consumption of different diverging junction's positions

Distance from station B (km)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
2	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
3	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
4	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
5	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)

Table 5.24 Capacity utilisation of different diverging junction's positions

Distance from station B (km)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
2	1.55	0.43	2760	2720
3	1.56	0.43	2780	2740
4	1.57	0.43	2800	2760
5	1.58	0.43	2820	2780

To sum up, the position of the diverging junction will impact on the capacity consumption only when the distance between the junction and the point that a train starts merged into a convoy is too close. It is similar to the impact of station spacing. If the diverging junction is placed closer to the merging point, the percentage of capacity consumption is increased allowing a lower number of trains inserted into the section.

5.4.12 Converging junction's position

Assuming that the converging junction is placed at different positions at 40 km, 50 km, 60 km, and 70 km from the station A.

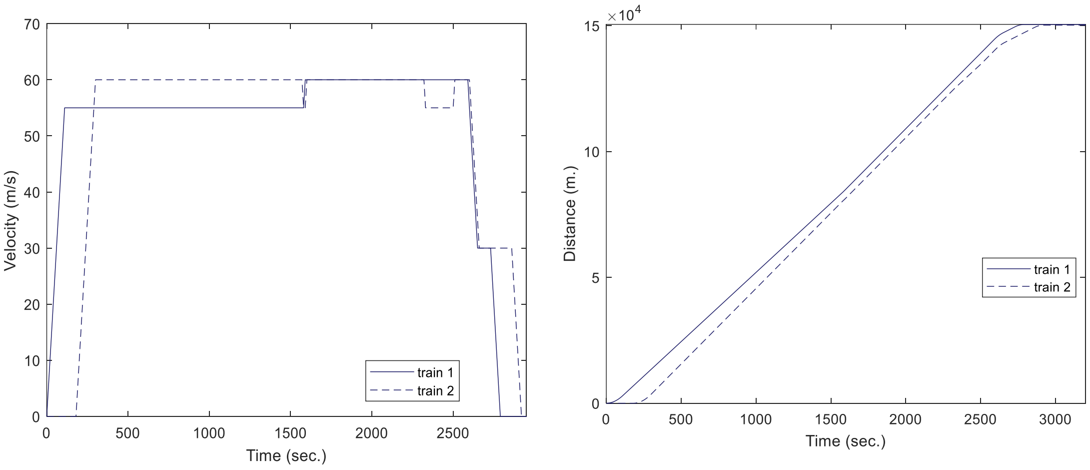


Figure 5.25 Distance and velocity profile of different positions of the converging junction

As the trains on the main route can pass the converging junction by $\mathrm{v}^{\mathrm{max}}$, they will not be forced to decelerate for passing the junction. Thus, the simulated distance and velocity profile of different positions of the converging junction are the same as shown in **Figure 5.25**.

According to the percentage of capacity consumption shown in **Table 5.25**, only the percentage of capacity consumption in the section B1 is different. This is due to the different headway time measured at the converging junction. The distance between trains is decreased with the increase of the distance for merged into the same convoy. If the junction is placed near the point that the trains start merged into a convoy, the headway time between them measured at the junction will be high increasing the percentage of capacity consumption. As a result, the percentage of unused capacity is lower allowing a lower number of trains operating on the same section. The capacity consumption in both section B2 and C (the sections behind the converging junction) shows the same results at 72.2% and 75% respectively.

Table 5.25 Capacity consumption of different converging junction's positions

Distance from station A (km)	**CC (%)**			**B1 (t/h)**	**B2 (t/h)**	**C (t/h)**
	B1	**B2**	**C**			
40	83.3	72.2	75.0	24 (24.0)	27 (27.7)	26 (26.7)
50	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
60	75.0	72.2	75.0	26 (26.7)	27 (27.7)	26 (26.7)
70	72.2	72.2	75.0	27 (27.7)	27 (27.7)	26 (26.7)

The simulated capacity utilisation of different positions of the converging junction is shown in **Table 5.26**. It is seen that the rate of velocity deviation, HET, and travel time result the same due to the same pattern for merged and split out from a convoy.

Table 5.26 Capacity utilisation of different converging junction's positions

Distance from station A (km)	**Velocity deviation (m/s)**	**HET**	**Travel time (sec)**	
			Leading train	**Following train**
40	1.55	0.43	2760	2720
50	1.55	0.43	2760	2720
60	1.55	0.43	2760	2720
70	1.55	0.43	2760	2720

In conclusion, this parameter has no impact on capacity consumption of any sections behind the converging junction. It only affects the capacity consumption of the section which has the converging junction placed within the section. A longer distance between the converging junction and the point that the trains start merged into the same convoy results a lower percentage of capacity consumption due to a lower headway time between trains measured when passing the junction. It is noted that the percentage of capacity consumption will result the same if the successive train could be transferred to the convoy state before passing the junction.

5.4.13 Train length

Basically, when trains have operated along the plain route, the leading train length does not relate to the minimum safe distance between trains. However, it relates to the minimum safe distance at a junction because a leading train must pass a junction by whole length before allowing a turnout switched for the next train.

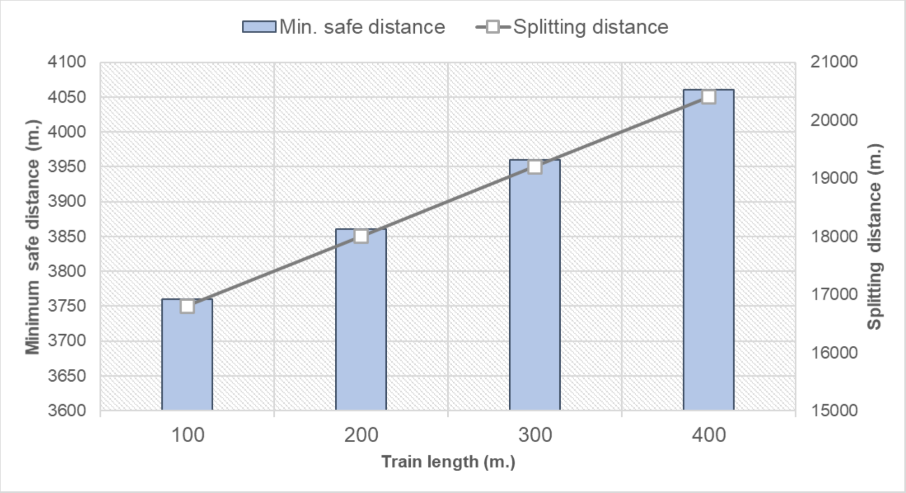
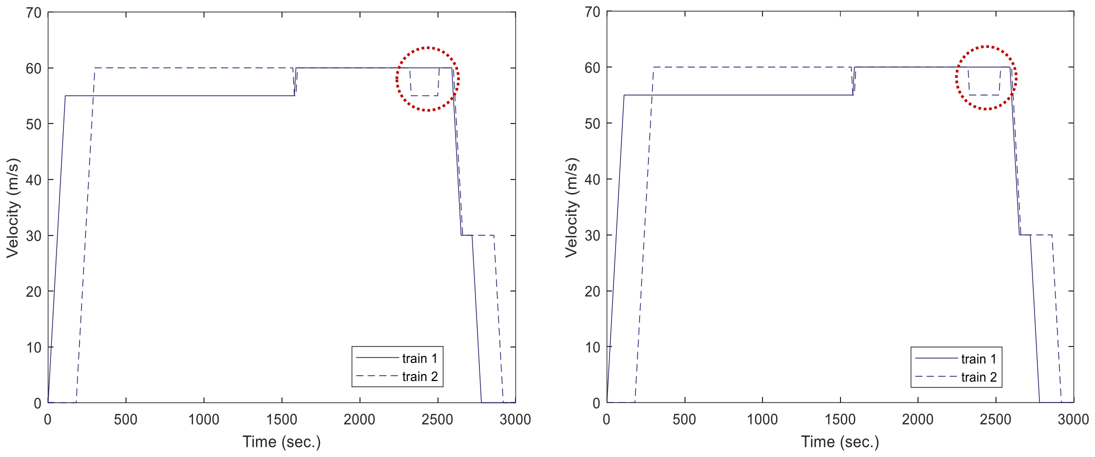


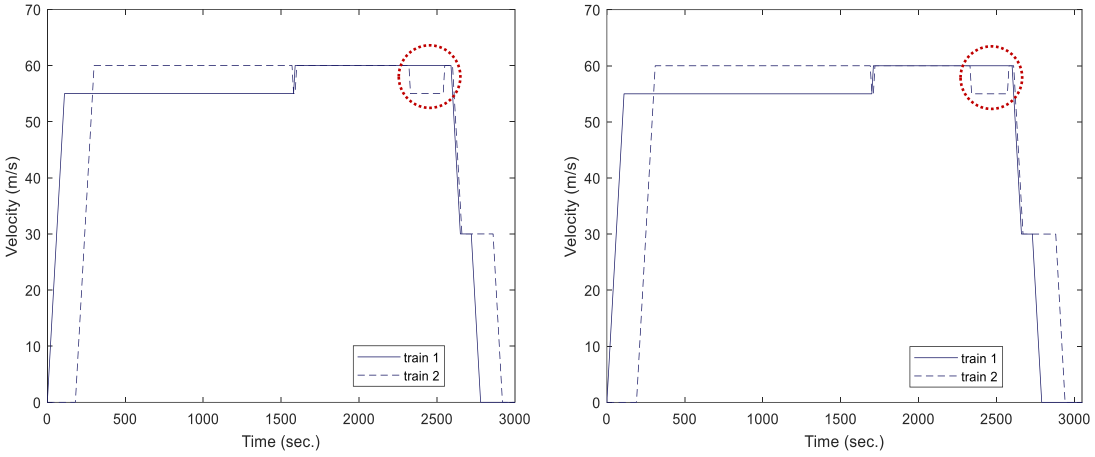
Figure 5.26 Relationship between a leading train's length and the minimum safe distance, and optimal splitting distance.

Referring to the equation used to calculate the minimum safe distance at a diverging junction (**Equation (3-11)**), the length of minimum safe distance is increased with the increase of a leading train's length. The relationship between the leading train's length and minimum safe distance is shown in **Figure 5.26**. With 100 m leading train's length, at least 3760 m separation distance is required for passing the junction. It is increased to about 4060 m if the leading train's length is increased to 400 m. In addition, the splitting distance is also increased. The simulated velocity profiles of different leading train length are shown in **Figure 5.27**. It could be confirmed that the leading train length relates to the splitting distance, in which a lower train length covers a shorter distance or a lower time to split out from a convoy.



(a) 100 m

(b) 200 m



(c) 300 m

(d) 400 m

Figure 5.27 Velocity profiles of different leading train's lengths

According to the percentage of capacity consumption of different train length shown in **Table 5.27**, the rate of capacity consumption in the section B1 is equal at 80.6% in the case of 100 – 300 m leading train length. It is slightly increased to 80.8% for 400 m leading train length. It is different because of the different minimum headway time between trains. With 400 m leading train length, the minimum headway time under the MBS is increased from 180 sec to 190 sec allowing 19 trains departing from station A. In the section B2 and C, 100 m and 200 m train's length shows the same percentage of capacity consumption due to the same minimum headway time at the junction,130 sec. The minimum headway time is increased from 130 sec to 140 sec if the leading train length is longer than 240 sec. Thus, the percentage of capacity consumption in the case of 300 m and 400 m train length is increased compared to capacity under a shorter leading train length.

Table 5.27 Capacity consumption of different leading train's lengths

Train length (m)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
100	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
200	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
300	80.6	77.8	80.6	24 (24.8)	25 (25.7)	24 (24.8)
400	80.8	76.1	76.7	23 (23.2)	25 (25.7)	24 (24.8)

According to the simulated capacity utilisation shown in **Table 5.28**. The rate of velocity deviation and HET is slightly different and tend to be increased with the increased of a leading train's length.

Table 5.28 Capacity utilisation of different leading train's lengths

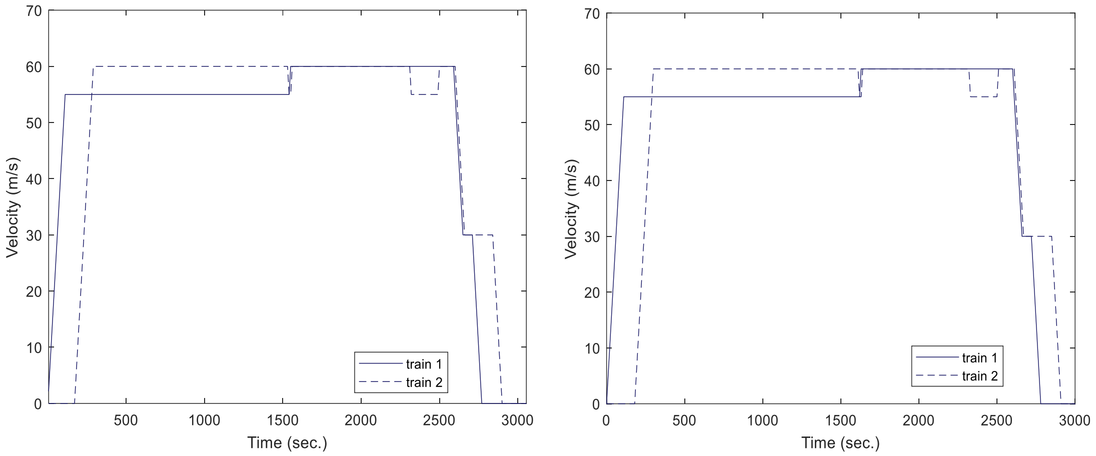
Train length (m)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
100	1.55	0.43	2760	2720
200	1.56	0.43	2760	2720
300	1.57	0.44	2760	2730
400	1.57	0.44	2770	2730

To sum up, a leading train's length directly relates to the minimum headway time required for passing a junction. A leading train must pass the junction by its whole length before allowing the turnout moved back and set for the next train to pass. A longer train length requires a longer separation distance when passing the junction. As a result, the headway time between trains is increased reducing the percentage of unused capacity. Consequently, the number of trains that could operate along the same section is lower.

5.4.14 Safety margin

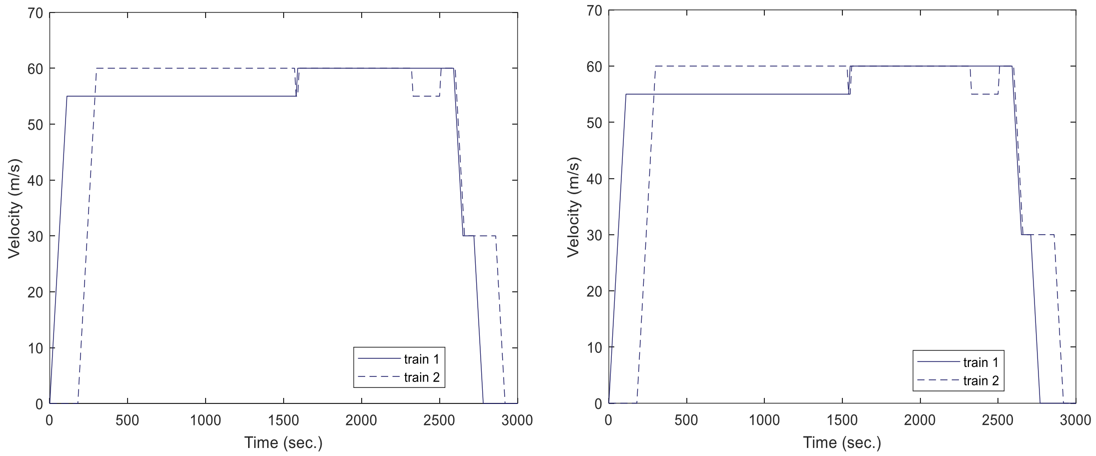
Safety margin refers to the compensated distance due to the system, communication, and driver response delay. It is added into the equation to calculate minimum safe distance between trains. To determine the impact of safety margin on capacity consumption, assuming that safety margin used to calculate the minimum safe distance is different ranged between 2000 m – 2800 m.

The simulated velocity profiles of different lengths of safety margin are shown in **Figure 5.28**. It is found that a following train has split out from a convoy covering the same spitting distance resulting the same shape of velocity profile. For example, in case of 2000 m safety margin, the headway time between trains when proceeding along the plain route is 50 sec. It has been extended to 120 sec when the trains have passed through the diverging junction. Compared to the case of 2400 m safety margin, the distance between trains must be extended from 60 sec to at least 130 sec. Thus, the extended headway time of both cases is equal at 70 sec. Consequently, the splitting distance of both cases is equal resulting the same shape of velocity profile when trains approach the junction.



(a) 2000 m

(b) 2200 m



(c) 2400 m

(d) 2800 m

Figure 5.28 Velocity profiles of different lengths of safety margin

The percentage of capacity consumption and the maximum number of trains in each section are shown in **Table 5.29**. The capacity consumption in the section B1 tends to be increased with the increase of safety margin. It means that a shorter safety margin allows a higher number of trains to be inserted in the section B1. The capacity consumption of 2400 m and 2600 m results the same rate at 80.6% because the minimum headway time under the MBS and VCS of both cases are equal at 180 sec and 60 sec respectively.

The capacity consumption in the section B2 and C shows the same trend as found in the section B1. It is increased with the increase of the length of safety margin. However, it is seen that the percentage of capacity consumption of 2000 m and 2200 m is not different. This is because, in both cases, the minimum headway time required for plain route and for passing the diverging junction are equal at 50 sec and 120 sec respectively. It is noted that the minimum headway time between trains with different lengths of safety margin is slightly different. For example, 112 sec and 119 sec minimum headway time are required for passing through the diverging junction in the case of 2000 m and 2200 m safety margin respectively. But, due to the increment of time step, which is increased by 10 sec, the minimum headway times for both cases are equal at 120 sec.

Table 5.29 Capacity consumption of different lengths of safety margin

Safety margin (m)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
2000	75.0	66.7	69.4	26 (26.7)	30 (30.0)	28 (28.8)
2200	77.8	66.7	69.4	25 (25.7)	30 (30.0)	28 (28.8)
2400	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
2600	80.6	77.8	80.6	24 (24.8)	25 (25.7)	24 (24.8)

The HET rate is increased with the increase of the length of safety margin due to a higher headway time required for passing the diverging junction (**Table 5.30**). Except the case of 2000 m safety margin, the HET rate is too high due to a lower headway time required when a couple of trains has operated on the plain route. At least 50 sec headway time is required for 2000 m safety margin while at least 60 sec required for the other cases.

Table 5.30 Capacity utilisation of different lengths of safety margin

Safety margin (m)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
2000	1.62	0.48	2760	2720
2200	1.59	0.41	2750	2700
2400	1.55	0.43	2760	2720
2600	1.51	0.44	2760	2730

It can be concluded that the length of safety margin impacts on the minimum headway time between trains. A shorter length of safety margin results a lower percentage of capacity consumption allowing a higher number of trains operating along the same route.

5.4.15 Turnout operation time

The turnout operation time refers to the time that the turnout switch has been set for the next train. In this test, it is assumed that the junction operation time varies between 10 sec – 16 sec. Referring to **Equation (3-11)**, the junction operation time is the parameter used to calculate the minimum safe distance required for passing a junction. A longer time that the turnout has set results a longer minimum safe distance. Due to a longer minimum safe distance, the splitting distance is also longer.

Figure 5.29 shows the relationship between junction operation time, and the minimum safe distance and the optimal splitting distance. With 12 sec operation time, at least 3760 m separation distance is required for passing a junction safely. It is increased to 4120 m when the turnout operation time increased to 24 sec. The simulated velocity profiles of trains under different turnout operation times are shown in **Figure 5.30**. It can be confirmed that the junction operation time impacts on the minimum safe distance required for passing through the diverging junction and the distance for splitting from a convoy. When the turnout operation time is higher, the minimum safe distance required for passing the diverging junction is also longer. Thus, a following train will proceed covering a longer time (or a longer distance) to split from a train convoy.

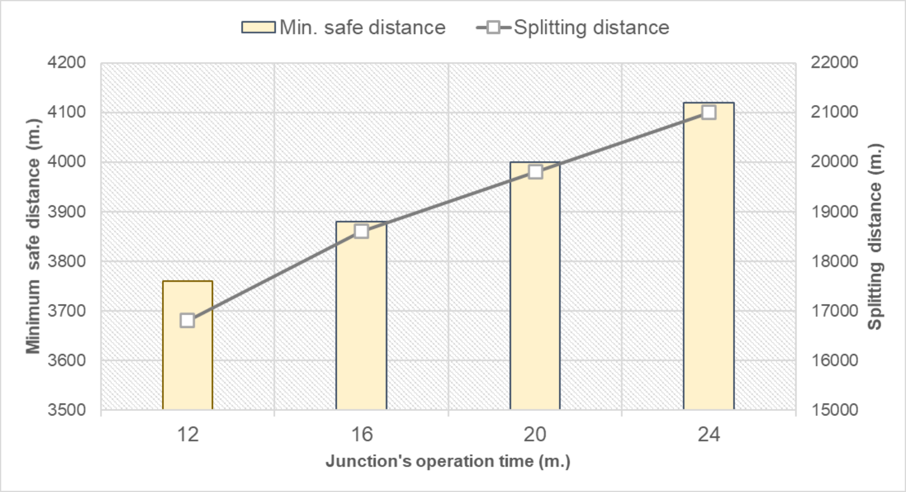
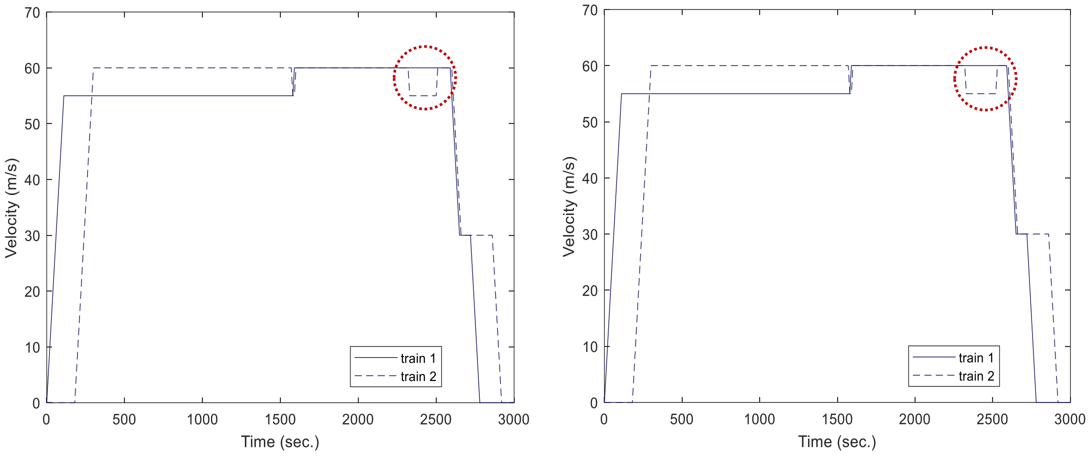


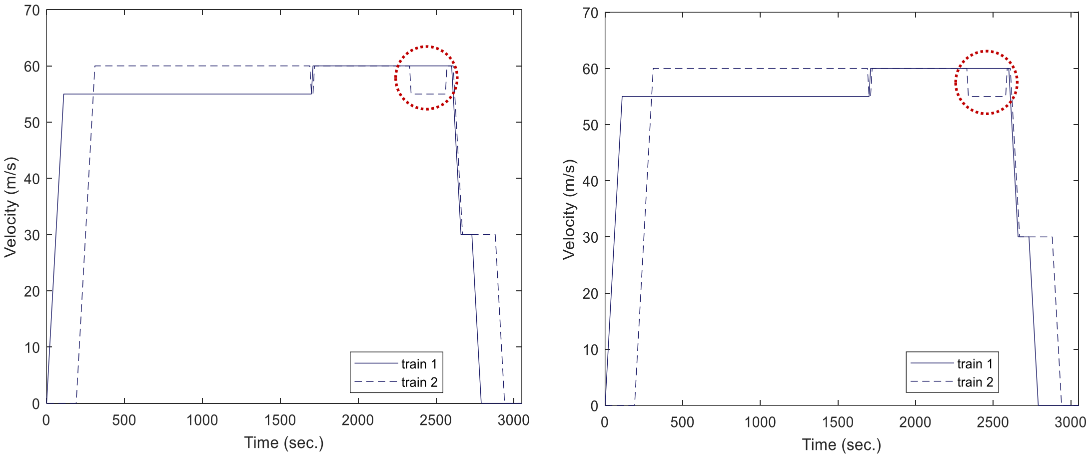
Figure 5.29 Relationship between junction operation time and the minimum safe distance required for passing the diverging junction

According to the capacity consumption presented in **Table 5.31**, it is seen that the capacity consumption in the section B1 is pretty the same at approximately 81%. However, the maximum number of trains that could operate within this section is different. In one hour defined time period, 24 trains can operate within the section B1 when the turnout operation time is 16 sec. It is reduced to 23 trains per hour when the turnout operation time is higher than 16 sec. This is because when the junction operation time is higher than 16 sec, the minimum dispatching headway time is increased to 190 sec. Thus, the number of trains departing from the station A is lower.



(a) 12 sec

(b) 16 sec



(c) 20 sec

(d) 24 sec

Figure 5.30 Velocity profiles of different junction operation times

The percentage of capacity consumption in the section B2 and C shows the same trend as occur in the section B1, but it is obviously different. Taking a longer time to move the turnout requires a longer headway time between trains. As a result, the headway time between trains when passing the junction is higher increasing the percentage of capacity consumption. Thus, the number of trains that can be inserted into the section B2 and C is lower.

Table 5.31 Capacity consumption of different junction operation times

Junction operation time (sec)	**CC (%)**			**B1 (t/h)**	**B2 (t/h)**	**C (t/h)**
	B1	**B2**	**C**			
12	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
16	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
20	80.8	74.2	76.4	23 (23.2)	24 (24.8)	24 (24.8)
24	80.8	74.2	76.4	23 (23.2)	24 (24.8)	24 (24.8)

The rate of HET is also higher due to a higher gap between the headway time at the splitting point and the diverging junction. The velocity deviation rate is increased with the increase of turnout operation time. This is because a following will operate by splitting velocity (normally lower than optimal velocity) covering a longer distance to split from a leading train.

Table 5.32 Capacity utilisation of different junction operation times

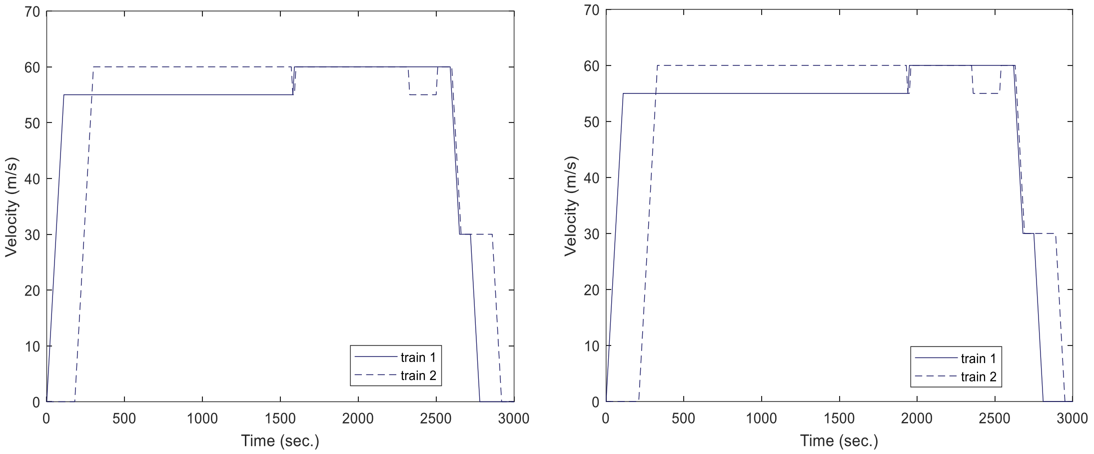
Junction operation time (sec)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
12	1.55	0.43	2760	2720
16	1.57	0.43	2760	2720
20	1.70	0.45	2770	2740
24	1.72	0.45	2770	2740

In conclusion, the turnout operation time directly impacts on the minimum headway time required for passing both converging and diverging junction. Using a higher time to set a turnout requires a longer braking distance. Thus, the headway time between trains is higher increasing the percentage of capacity consumption. As a result, a lower number of trains can be inserted reducing the route capacity.

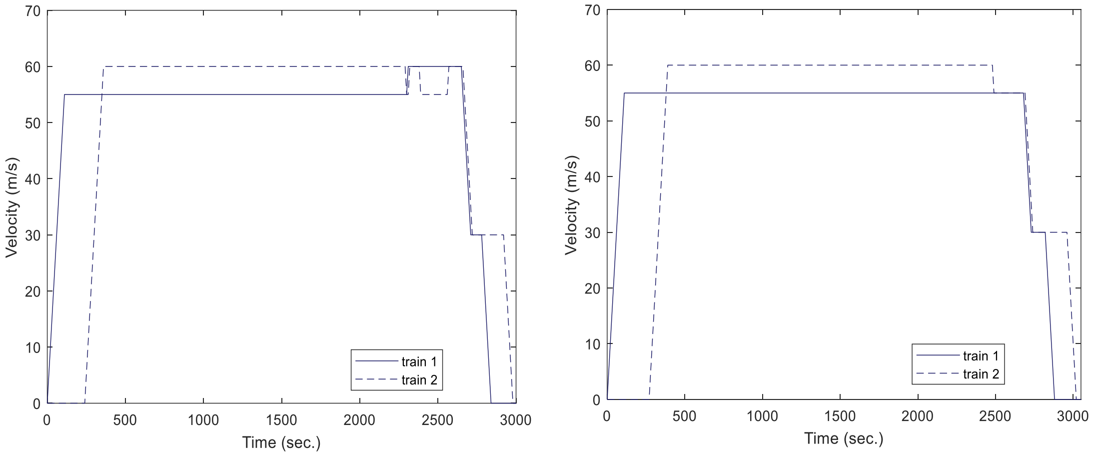
5.4.16 Dispatching time

Assuming that the trains depart from station A by different dispatching times ranged between 180 sec – 270 sec and then have proceeded by the same operational parameters to station B. A lower dispatching time means a shorter distance between trains when they start merged into the same convoy. Therefore, a couple of trains could be transferred to the convoy state earlier.

The simulated velocity profiles of trains with different dispatching headway times are shown in **Figure 5.31**. It is found that if the successive trains start merged into the same convoy when the headway time between them is too close, the trains need a shorter distance for merged into the convoy. As a result, the distance that both trains have operated by the same velocity is increased. Only the trains in the last case, 270 sec dispatching headway, cannot be transferred to the convoy state before reaching the splitting point.



(a) 180 sec (b) 210 sec



(c) 240 sec (d) 270 sec

Figure 5.31 Velocity profiles of different dispatching headways

The percentage of capacity consumption and the maximum number of trains that could operate in each section are shown in **Table 5.33**. It is seen that the percentage of capacity consumption is decreased with the increase of dispatching headway time. However, it is decreased just because the number of trains departing from the station A is lower. With 180 sec dispatching headway time, 24 trains/hour can operate within the section B1. It is reduced to 20 trains/hour when the dispatching headway time is increased from 180 sec to 270 sec. This is because, for a higher dispatching headway time, the headway time between trains measured at the same point is higher reducing the number of trains operating within the section.

The maximum number of trains in the section B2 and C is equal because of the same headway time when trains have coupled as the same convoy and when they have passed the diverging junction. However, the capacity consumption results the different rates due to the different number of trains departing from the station A.

Table 5.33 Capacity consumption of different dispatching times

Dispatching time (sec)	CC (%)			B1 (t/h)	B2 (t/h)	C (t/h)
	B1	B2	C			
180	80.6	72.2	75.0	24 (24.8)	27 (27.7)	26 (26.7)
210	75.0	59.4	63.6	22 (22.5)	27 (27.7)	26 (26.7)
240	72.8	52.2	56.1	20 (20.6)	27 (27.7)	26 (26.7)
270	63.1	45.6	48.6	20 (20.6)	27 (27.7)	26 (26.7)

Table 5.34 shows the rate of capacity utilisation of different dispatching time. The rate of velocity deviation is increased with the increase of the dispatching headway time because a leading train needs to operate by its merging velocity, which is lower than its optimal velocity for a longer distance to be merged into the same convoy with its following train. Due to a longer distance that it has operated by merging velocity, its travel time is also increased. Basically, the HET rate for 180 sec – 210 sec headway time should be the same due to the same headway times measured at the splitting point and the diverging junction. However, the HET shows the different rates due to the different number of trains departing from the origin station.

Table 5.34 Capacity utilisation of different dispatching times

Dispatching time (sec)	Velocity deviation (m/s)	HET	Travel time (sec)	
			Leading train	Following train
180	1.55	0.43	2760	2720
210	1.86	0.43	2790	2720
240	2.17	0.43	2820	2720
270	2.47	0.31	2860	2740

To sum up, the dispatching headway time directly relates to the distance that a couple of trains used to be merged into the same convoy. Dispatching from station by keeping a lower headway time between trains could help trains to be transferred to the convoy state earlier increasing the maximum number of trains that could operate within the same section.

5.5 Summary

In this chapter, the impact of a parameter on route capacity is determined. The trains are merged into convoys and operate under the VCS using different values. The rate of capacity consumption is compared for identifying whether a parameter impacts on route capacity. The capacity utilization including the maximum number of trains proceeding on each section, velocity deviation, timetable heterogeneity, and travel time are evaluated to determine how each parameter impacts the route capacity.

According to the simulated results, it is found that the route capacity could be increased if trains could be transferred into the convoy state earlier. To transferring trains into the convoy state earlier, there are many solutions such as using a higher braking rate, merging trains with a higher merging velocity gap, and operating with a higher velocity. Most of parameters impact the route capacity due to the number of trains operating along the same route. A shorter distance required when trains are merged into the same convoy results a higher route capacity. So, the rate of capacity consumption is decreased (the rate of unused capacity is increased) as the decrease of minimum safe distance between trains. Thus, a parameter used in the equation to calculate the minimum safe distance such as braking rate, operating velocity impacts on route capacity.

The relationship between unused capacity and capacity utilization is summarized as shown in **Table 5.35**. It is seen that the number of trains operate within the same section directly relates to the rate of unused capacity. For example, using a higher braking rate increases the rate of unused capacity. As a result, a higher number of trains could operate along the same route section. The velocity deviation relates to capacity consumption in some parameters including operating braking rate, operating velocity, junction velocity limit, train length, and junction operation time. The rate of velocity deviation is higher reducing the rate of unused capacity because a train proceed by velocity lowering than its optimal velocity (target velocity). This is due to a longer safe distance required at a junction that will force a following train operate by a lower velocity for a longer time to extend the distance between trains. The rate of timetable HET and travel time also impact on rate of capacity consumption in some parameters including operating braking rate, junction velocity limit, train length, and junction operation time. These parameters relate to the minimum safe distance required at a diverging junction. It could be concluded that the rate of unused capacity is decreased as the increase of minimum safe distance at a diverging junction.

Table 5.35 The relationship between the unused capacity and capacity utilisation

Parameter	Indicator	Unused capacity			Max. number of trains			Velocity deviation	HET	Travel time
		B1	B2	C	B1	B2	C			
1. No of trains in convoy	More trains	↑	↑	↑	✓	✓	✓	✕	✕	-
2. Route length	Longer route length	↑	NC	NC	✓	✕	✕	✕	✕	-
3. Max. braking rate	Higher max. braking rate	↑	↑	↑	✓	✓	✓	✕	✕	✕
4. Operating braking rate	Higher operating braking rate	NC	NC	↑	✕	✕	✓	✓	✓	✓
5. Merging velocity gap	Higher gap	↑	NC	NC	✓	✕	✕	✕	✕	✕
6. Merging velocity	Lower merging velocity	↑	NC	NC	✓	✕	✕	✕	✕	✕
7. Operating velocity	Lower operating velocity	↑	↑	↑	✓	✓	✓	✓	✕	-
8. Splitting velocity gap	Higher gap	NC	NC	NC	✕	✕	✕	✕	✕	✕
9. Splitting velocity	Higher splitting velocity	NC	NC	NC	✕	✕	✕	✕	✕	✕
10. Junction velocity limit	Higher velocity limit	↑	↑	↑	✓	✓	✓	✓	✓	✓
11. Diverging junction position	Longer (measured from next station)	NC	NC	NC	✕	✕	✕	✕	✕	✕
12. Converging junction position	Longer (measured from merging point)	↑	NC	NC	✓	✕	✕	✕	✕	✕
13. Train length	Shorter train	NC	↑	↑	✕	✓	✓	✓	✓	✓
14. Safety margin	Shorter safety margin	↑	↑	↑	✓	✓	✓	✕	✕	✕
15. Junction operation time	Lower time	↑	↑	↑	✓	✓	✓	✓	✓	✓
16. Dispatching time	Higher headway time	↑	↑	↑	✓	✓	✓	✕	✕	-

Remark: ↑ increased NC = No change ✓ related ✕ not related - Not considered

Chapter 6
Applying the VCS for increasing route capacity: The approach used in the planning state

6.1 Introduction

According to previous studies of train control operating under the VCS (Flammini et al., 2018; Henke, Ticht, et al., 2008; Mitchell, 2016; Quaglietta & Goverde, 2019a; J. Ye et al., 2013), it could be concluded that the route capacity is increased just because the headway time between trains is reduced. However, it does not mean that the real capacity or the number of trains that can operate within a defined time period is increased. Applying the VCS may result the in same as obtained from other signaling controls. Thus, creating a train convoy may increase the headway time in front of the convoy but the headway time may not high enough to insert an extra train to operate along the same route. To increase route capacity (the number of trains that could operate along the same route), the idea is to merge a group of trains into the same convoy for extending the headway time that is high enough for inserting an extra train to operate into the same route.

As stated in the MOVINGRAIL report, the roadmap for virtual coupling by Goverde (2020), a converging junction could be considered as the conflict point between trains from different routes. The route capacity will be decreased at this point due to a longer distance required for passing. Normally under the MBS, the sequence of trains passing a junction is managed by the control center. In the case that trains from different routes reach the junction at almost the same time, a following train will need to wait until the route is clear and set for the next train to pass. It is different from the movement of trains under the VCS. When trains have proceeded as a train convoy, it can be considered as a single train and can pass a junction with no requirement to split out from a convoy. However, the distance between a train on the main route and an insert train from other routes must be at least the absolute braking distance. Currently, only the approaches applied for controlling trains under the VCS have been developed. They are introduced mainly in order to minimize the distance between trains. However, there are a few research suggesting when the VCS will be applied.

On the busy route where the capacity consumption of the route is close to the maximum capacity, any trains from other routes cannot be inserted because there is no available gap. Applying the VCS for building a train convoy will increase the headway time in front of and/or behind a train convoy. To increase route capacity, the VCS should be used to control trains when the number of trains which will operate on the same route exceeds than the maximum capacity under the main signaling control. The idea is to build some trains as a train convoy before passing a converging junction for providing the headway time that is high enough to insert an extra train. However, we do not know when trains should be built as a convoy and controlled under the VCS, how many trains should be built into the same convoy, and what is the optimal velocity that trains should operate for merged into the convoy.

6.2 Objective

It is well known that the VCS could be used to reduce the headway time between trains. However, it is not clear that when and how the VCS should be used. Following the roadmap of the VCS mentioned in MOVINGRAIL report (Goverde, 2020), the important railway control role that needs to be clearly determined is to manage trains passing through a converging junction. The objective of this chapter is to increase route capacity by building some trains as a train convoy for passing through a converging junction. The headway time in front of the convoy or the headway time behind the convoy when passing a junction are increased allowing an extra train to be inserted.

In this chapter, the approach to determine whether the trains should be built as a train convoy, to identify which trains should be built into the same convoy, and to calculate the optimal merging velocity is proposed. This approach will be to create a new timetable in relation to the number of trains that will operate along the same route. The capacity in terms of the number of trains in one hour with and without the VCS is compared in order to evaluate the effectiveness of the proposed approaches.

6.3 Methodology

The flowchart in **Figure *3.19*** is proposed to determine whether the VCS should be used to merge a group of trains into a train convoy. This could help the planner to plan the timetable by:

(1) Suggesting whether the VCS should be applied to create a train convoy (**Section 3.4.1**).

(2) Identifying which trains will be built into a train convoy (**Section 3.4.2.2**).

(3) How many trains will be built into the same convoy (**Section 3.4.2.4**).

(4) Suggesting when the trains should start merged into a train convoy (**Section 3.4.2.6**).

(5) Calculating the optimal velocity that trains should proceed for merged into a train convoy (**Section 3.4.2.7**).

6.4 Test case and simulation results

The effectiveness of the proposed approach is determined via the test case below. Assuming that, within 15 min, six trains will depart from station maintaining 3 min departing headway time. They will operate based on the operational parameters shown in **Table 6.1**. The trains from route B will be merged into the route A via the converging junction placed at 90 km away from the origin station. The movement of trains in two test cases are simulated.

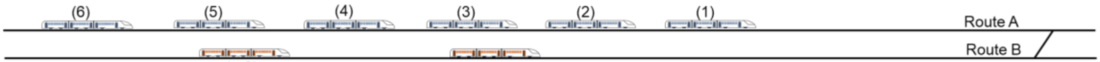
Table 6.1 Operational parameters

Parameters		
1) Velocity limit along the route ($\mathbf{v^{max}}$)	70	m/s
2) Operating velocity before merged into a convoy ($\mathbf{v^{opt}}$)	60	m/s
3) Velocity limit at the converging junction ($\mathbf{v^{maxp}}$)	60	m/s
4) Time step ($\Delta\mathbf{t}$)	10	sec
5) Safety margin ($\mathbf{SM}$)	2.4	km
6) Maximum acceleration rate ($\mathbf{a_k^{max}}$)	0.5	m/s^2
7) Maximum braking rate ($\mathbf{b_k^{max}}$)	0.5	m/s^2
8) Turnout switch operation time ($\mathbf{T^{pnt}}$)	12	sec
9) Converging junction location ($\mathbf{x^{cvr}}$)	90	km
10) Merging starting point (away from the converging junction)	50	km
11) Safe zone ($\Delta\mathbf{x^{sz}}$)	6	km
12) Train length ($\mathbf{l_k}, \mathbf{l_m}$)	100	m
13) Minimum headway time under the MBS ($\Delta\mathbf{T^{min}}$)	180	sec

6.4.1 Test case 1: inserting a single train

Assuming that six trains on the route A proceed by the same velocity at 60 m/s maintaining 3 min headway time away from their adjacent train. They approach the converging junction where two trains from the route B will be converged to proceed on the route A. Based on original timetable, the trains will reach the converging junction by the estimated reaching time shown in **Figure 6.1**. It is noted that the headway time between a train on the main route and an inserted train must not be less than the permissible headway time at 180 sec. However, the estimated headway time from the train m1 to the train 3 and train 4, and from the train m2 to the train 5 and train 6 are less than the minimum headway time. Thus, the train m1 and m2 could not be inserted into the route A because the headway time between trains on the main route is equal to the minimum headway time under the MBS. To increase the headway time to insert the extra two trains, the trains on the route A should be merged as the convoys in order to increase headway time that is high enough to insert both trains into the route A safely.

The involved trains and the optimal merging velocity are calculated by following the approach shown in **Section 3.4**. By comparing the m1’s estimated reaching time to the estimated reaching time of six trains on the route A, the headway time from train m1 to train 3 and train 4 is lower than minimum headway time under the MBS.

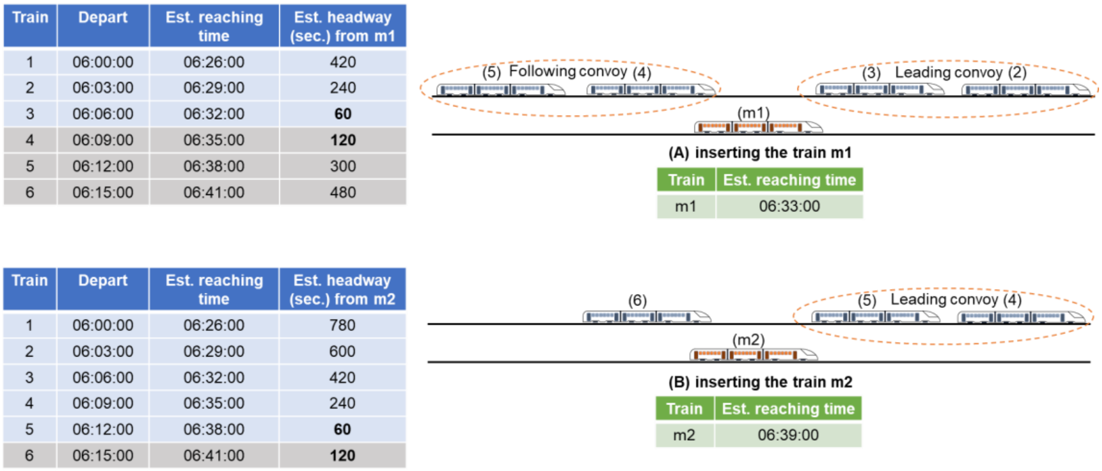


Train	Est. reaching time
m1	06:33:00
m2	06:39:00

Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	06:29:00
3	06:06:00	06:32:00
4	06:09:00	06:35:00
5	06:12:00	06:38:00
6	06:15:00	06:41:00

Figure 6.1 Estimated reaching time based on the original timetable: Case 1

The headway times from the train m1 to six trains on the route A are shown in **Figure 6.2 (A)**. The headway time between the train m1 and the train 3 is only 60 sec but at least 180 sec is required for passing the junction safely. Thus, the headway time behind the train 3 should be increased by at least 120 sec (or at least 7200 m). In this case, the train 3 will be built into the same convoy with the reference train 2 in order to increase headway time for inserting the train m1.



Train	Depart	Est. reaching time	Est. headway (sec.) from m1
1	06:00:00	06:26:00	420
2	06:03:00	06:29:00	240
3	06:06:00	06:32:00	**60**
4	06:09:00	06:35:00	**120**
5	06:12:00	06:38:00	300
6	06:15:00	06:41:00	480

(A) inserting the train m1

Train	Est. reaching time
m1	06:33:00

Train	Depart	Est. reaching time	Est. headway (sec.) from m2
1	06:00:00	06:26:00	780
2	06:03:00	06:29:00	600
3	06:06:00	06:32:00	420
4	06:09:00	06:35:00	240
5	06:12:00	06:38:00	**60**
6	06:15:00	06:41:00	**120**

(B) inserting the train m2

Train	Est. reaching time
m2	06:39:00

Figure 6.2 Estimated headway times from inserted trains to trains on route A

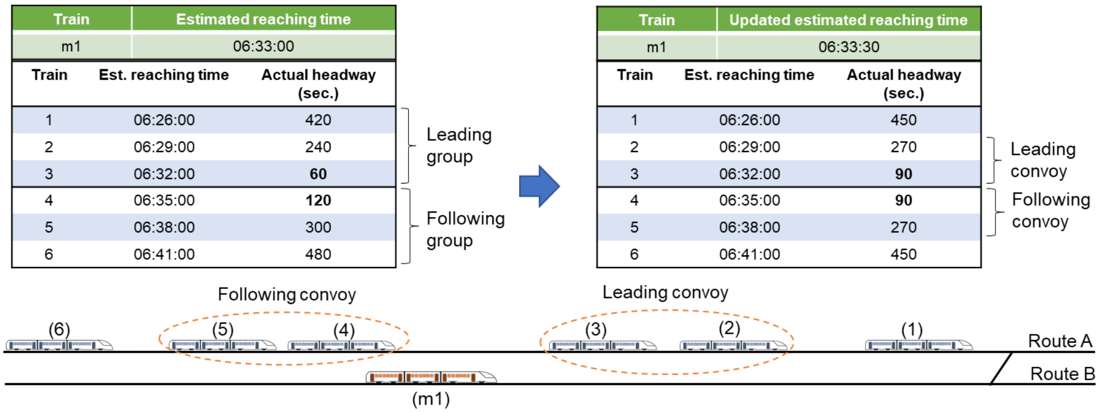
It is assumed that the reference train 2 (the first train in the leading convoy) proceeds by its optimal velocity at 60 m/s through the merging state. The train 3 will start merged when reaching the merging point which is set at 44 km away from the beginning of the safe zone. Thus, the optimal merging velocity for the train 3 is

$$v_3^{mer} = v_2^{mer}\Big/\left(1-\frac{\Delta x_{Lead}^{ext}}{\Delta x^{mer}}\right) = 60\Big/\left(1-\frac{7200}{44000}\right) = 72\ \mathrm{m/s}$$

However, it is higher than the maximum velocity restricted along the route A. It means that the train 3 could accelerate to 70 m/s at maximum. Thus, the optimal merging velocity that the train 2 and train 3 coupled together as the leading convoy is 60 m/s and 70 m/s respectively. The estimated extended headway time behind the leading convoy is

$$\Delta t_{Lead}^{etg} = \left(44000\left(1-\frac{60}{70}\right)\right)/70 = 90\ \mathrm{sec}$$

Thus, the inserted train m1 should slow down for maintaining safe headway time away from the train 3. 30 sec residual time gap will be added to the estimated reaching time of the train m1, in which the velocity profile of the train m1 is re-created. The estimated reaching time of the train m1 is changed to 06:33:30. **Figure 6.3** shows the updated estimated headway time from the train m1 to the six trains on the main route. It is found that the headway time between train m1 and train 3 before merged into a train convoy is increased from 60 sec to 90 sec while the headway time from the train m1 to the first train in the following convoy (train 4) is reduced from 120 sec to 90 sec. Thus, the headway time between train m1 and train 3 will be increased from 90 sec to 180 sec when passing the converging junction.



Train	Estimated reaching time	
m1	06:33:00	
Train	**Est. reaching time**	**Actual headway (sec.)**
1	06:26:00	420
2	06:29:00	240
3	06:32:00	**60**
4	06:35:00	**120**
5	06:38:00	300
6	06:41:00	480

Train	Updated estimated reaching time	
m1	06:33:30	
Train	**Est. reaching time**	**Actual headway (sec.)**
1	06:26:00	450
2	06:29:00	270
3	06:32:00	**90**
4	06:35:00	**90**
5	06:38:00	270
6	06:41:00	450

Figure 6.3 Updated estimated headway time from the train m1

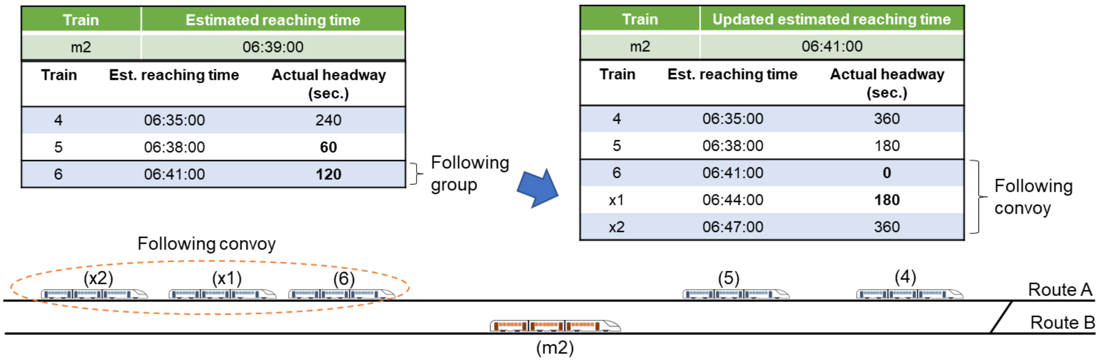
For the following convoy, at least 90 sec extra headway time (or approximately 5.4 km separation distance) in front of the train 4 is required. The train 4 will start merged into the following convoy with the reference train 5 when reaching the merging point. Assuming that the train 5 operates by optimal velocity at 60 m/s through the merging state. The optimal merging velocity for the train 4 should not be higher than

$$\mathrm{v}_4^{\mathrm{mer}} = \mathrm{v}_5^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{Follow}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{5400}{44000}\right)\right) = 53\ \mathrm{m/s}$$

Thus, the train 2, train 3, train 4, and train 5 will be built into convoys by **60 m/s, 70 m/s, 53 m/s, and 60 m/s** respectively to increase the time gap for inserting the train m1.

According to the headway time summarized in **Figure 6.4**, it is seen that the headway time from the inserted train m2 to the train 5 is 60 sec. It is less than the minimum permissible headway time for passing the junction. To insert the train m2 into the route A, the train 5 should normally be built as a train convoy with the train 4. However, the train 4 and train 5 are already built in another convoy. In this case, there are no trains built as the leading convoy in front of the inserted train m2. Thus, the estimated reaching time of the train m2 is changed from 06:30:00 to 06:41:00 for maintaining safe headway time from the train 4.

The estimated headway time from the train m2 to the trains on the route A is updated as shown in the right table in **Figure 6.4**. It is seen that the train m2 and train 6 will reach the converging junction at the same time. Thus, at least 180 sec is required on front of the train 6. However, there are no train following the train 6 within 15 min defined time period. In this case, the train 6 will be merged as a train convoy with the trains in the next time period.



Train	Estimated reaching time	
m2	06:39:00	
Train	**Est. reaching time**	**Actual headway (sec.)**
4	06:35:00	240
5	06:38:00	**60**
6	06:41:00	**120**

Train	Updated estimated reaching time	
m2	06:41:00	
Train	**Est. reaching time**	**Actual headway (sec.)**
4	06:35:00	360
5	06:38:00	180
6	06:41:00	**0**
x1	06:44:00	**180**
x2	06:47:00	360

Figure 6.4 Updated estimated headway time from the train m2

Referring to the updated estimated reaching time in **Figure 6.4**, It is seen that the headway time from the train m2 to the train 6 and train x1 is lower than the minimum headway time. In this case, both train 6 and train x1 needs to decelerate to be built into the same convoy with the reference train x2. The optimal merging velocity for the train 6 is

$$v_6^{\mathrm{mer}} = v_{x2}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta x_{\mathrm{Follow}}^{\mathrm{ext}}}{\Delta x^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{10800}{44000}\right)\right) = 48\ \mathrm{m/s}$$

and the optimal velocity gap between successive trains is $(v_{x2}^{\mathrm{mer}} - v_6^{\mathrm{mer}})/K = (60 - 48)/2 = 6\ \mathrm{m/s}$. The optimal merging velocity of the trains in the convoy behind the train m2 is

$$v_6^{\mathrm{mer}} = 48\ \mathrm{m/s}$$

$$v_{x1}^{\mathrm{mer}} = \max[(48 + 6), 60] = 54\ \mathrm{m/s}$$

$$v_{x2}^{\mathrm{mer}} = \max[(54 + 6), 60] = 60\ \mathrm{m/s}$$

Therefore, the train 6, train x1, and train x2 will operate to be built into the following convoy by **48 m/s, 51 m/s, and 60 m/s** respectively.

Figure 6.5 shows the simulated distance-time and velocity-time profiles of three convoys built for inserting the train m1 and train m2. The train 1 is not built as in a convoy and still operate under the MBS. The train 2 and train 3 are merged as the leading convoy while the train 4 and train 5 are built into the following convoy for increasing the time gap to insert the train m1. It is seen that the headway time between train 3 and train 4 when passing the junction is extended from 180 sec to 370 sec that is high enough for inserting the train m1 into the main route safely.

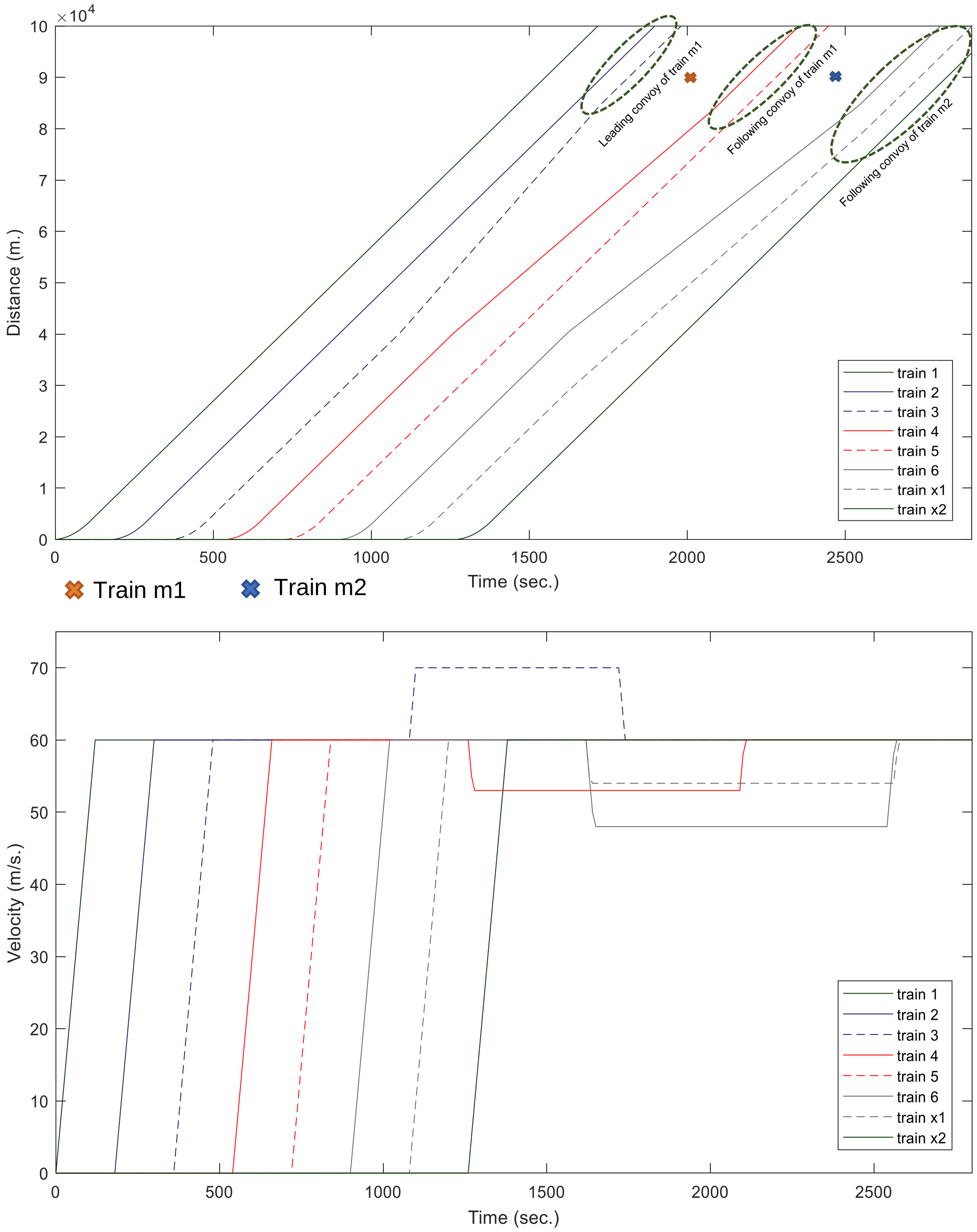
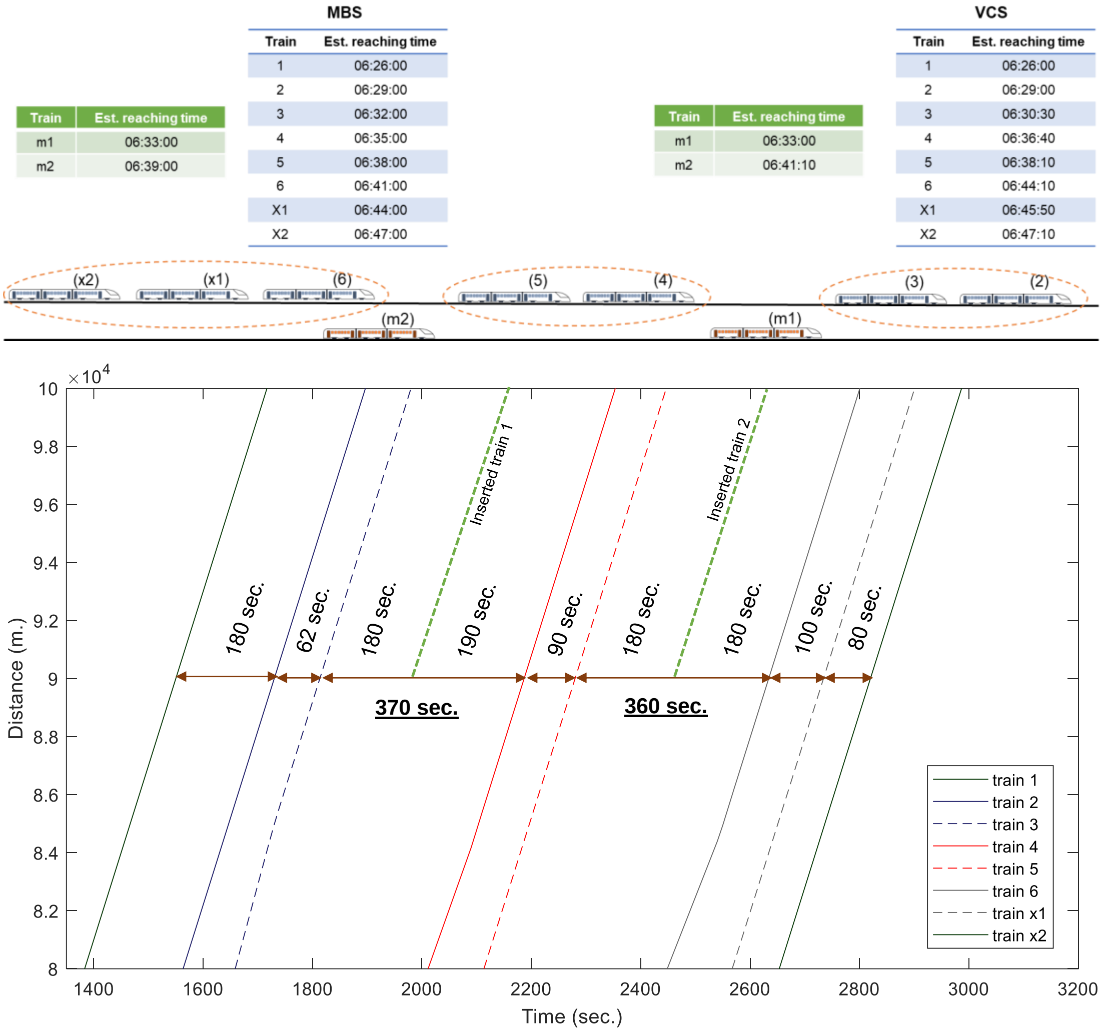


Figure 6.5 Simulated distance and velocity profile of trains in case 1

To insert the train m2 into the route A, three trains (train 6, train x1, and train x2) are merged together as the following convoy. The time gap in front of the convoy is increased from 180 sec to 360 sec which is safe to insert the train m2 into the route A.



Train	Est. reaching time
m1	06:33:00
m2	06:39:00

MBS

Train	Est. reaching time
1	06:26:00
2	06:29:00
3	06:32:00
4	06:35:00
5	06:38:00
6	06:41:00
X1	06:44:00
X2	06:47:00

Train	Est. reaching time
m1	06:33:00
m2	06:41:10

VCS

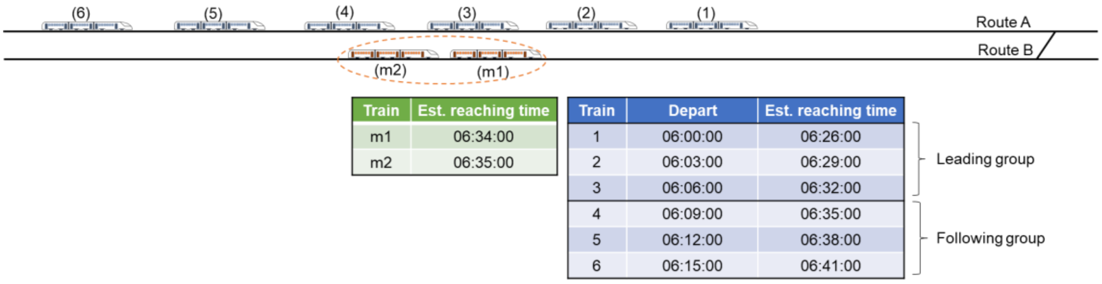
Train	Est. reaching time
1	06:26:00
2	06:29:00
3	06:30:30
4	06:36:40
5	06:38:10
6	06:44:10
X1	06:45:50
X2	06:47:10

Figure 6.6 headway times between trains when passing converging junction: Case 1

It could be concluded that by following the proposed approach for creating a new timetable (**Section 3.4**), the route capacity in terms of the number of trains that cab operate along the same route is increased compared to the capacity under the MBS. Some trains will be merged as a train convoy in order to increase the headway time between trains allowing more trains to be inserted into the same route.

6.4.2 Test case 2: inserting a convoy

Assuming that the train m1 and train m2 have been coupled as the same convoy maintaining 1 min headway time. It (the inserted convoy) will reach the junction and will be inserted into the route A by the estimated time shown in **Figure 6.7**. By comparing the estimated reaching time of the inserted convoy with the trains on the route A, it is found that only the estimated headway time between the train 3 and the inserted train m1 is lower than minimum headway time at 180 sec.



Train	Est. reaching time
m1	06:34:00
m2	06:35:00

Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	06:29:00
3	06:06:00	06:32:00
4	06:09:00	06:35:00
5	06:12:00	06:38:00
6	06:15:00	06:41:00

Figure 6.7 Estimated reaching time based on the original timetable: Case 2

In this case, the train 3 should accelerate to be coupled together with the reference train 2 for lengthening the time gap separated from the train m1. The time gap behind the train 3 should be extended from 120 sec to at least 180 sec. Thus, the optimal merging velocity of the train 3 is

$$\mathrm{v}_3^{\mathrm{mer}} = \mathrm{v}_2^{\mathrm{mer}} / \left(1 - \frac{\Delta\mathrm{x}_{\mathrm{Lead}}^{\mathrm{ext}}}{\Delta\mathrm{x}^{\mathrm{mer}}}\right) = 60/\left(1 - \frac{3600}{44000}\right) = 66\ \mathrm{m/s}$$

To extend the time gap for 60 sec, the train 3 should accelerate to at least 66 m/s for merged into the same convoy with the train 2 which will proceed by 60 m/s. The last train in the inserted convoy (train m2) will reach the junction by 06:35:00. It will reach the junction at the same time with the train 4. Its headway time away from both train 4 and train 5 is lower than permissible headway time for passing the junction. Thus, both train 4 and train 5 should decelerate to be merged as the same convoy with the reference train 6 in order to extend the time gap in front of the train 4. The optimal merging velocity of the train 4 is

$$\mathrm{v}_4^{\mathrm{mer}} = \mathrm{v}_6^{\mathrm{mer}} / \left(1 + \left(\frac{\Delta\mathrm{x}_{\mathrm{Follow}}^{\mathrm{ext}}}{\Delta\mathrm{x}^{\mathrm{mer}}}\right)\right) = 60/\left(1 + \left(\frac{10800}{44000}\right)\right) = 48\ \mathrm{m/s}$$

The different merging velocity between the first and last train in the following convoy is 12 m/s. So, the optimal velocity difference between successive trains is $(\mathrm{v}_6^{\mathrm{mer}} - \mathrm{v}_4^{\mathrm{mer}})/\mathrm{K} = (60 - 48)/2 = 6\ \mathrm{m/s}$. The optimal merging velocity of the trains in the following convoy is

$$\mathrm{v}_4^{\mathrm{mer}} = 48\ \mathrm{m/s}$$

$$\mathrm{v}_5^{\mathrm{mer}} = \max[(48 + 6), 60] = 54\ \mathrm{m/s}$$

$$\mathrm{v}_6^{\mathrm{mer}} = \max[(54 + 6), 60] = 60\ \mathrm{m/s}$$

Thus, the train 2, train 3, train 4, train 5, and train 6 will be built into two convoys by using **60 m/s, 66 m/s, 48 m/s, 54 m/s and 60 m/s** optimal merging velocity respectively.

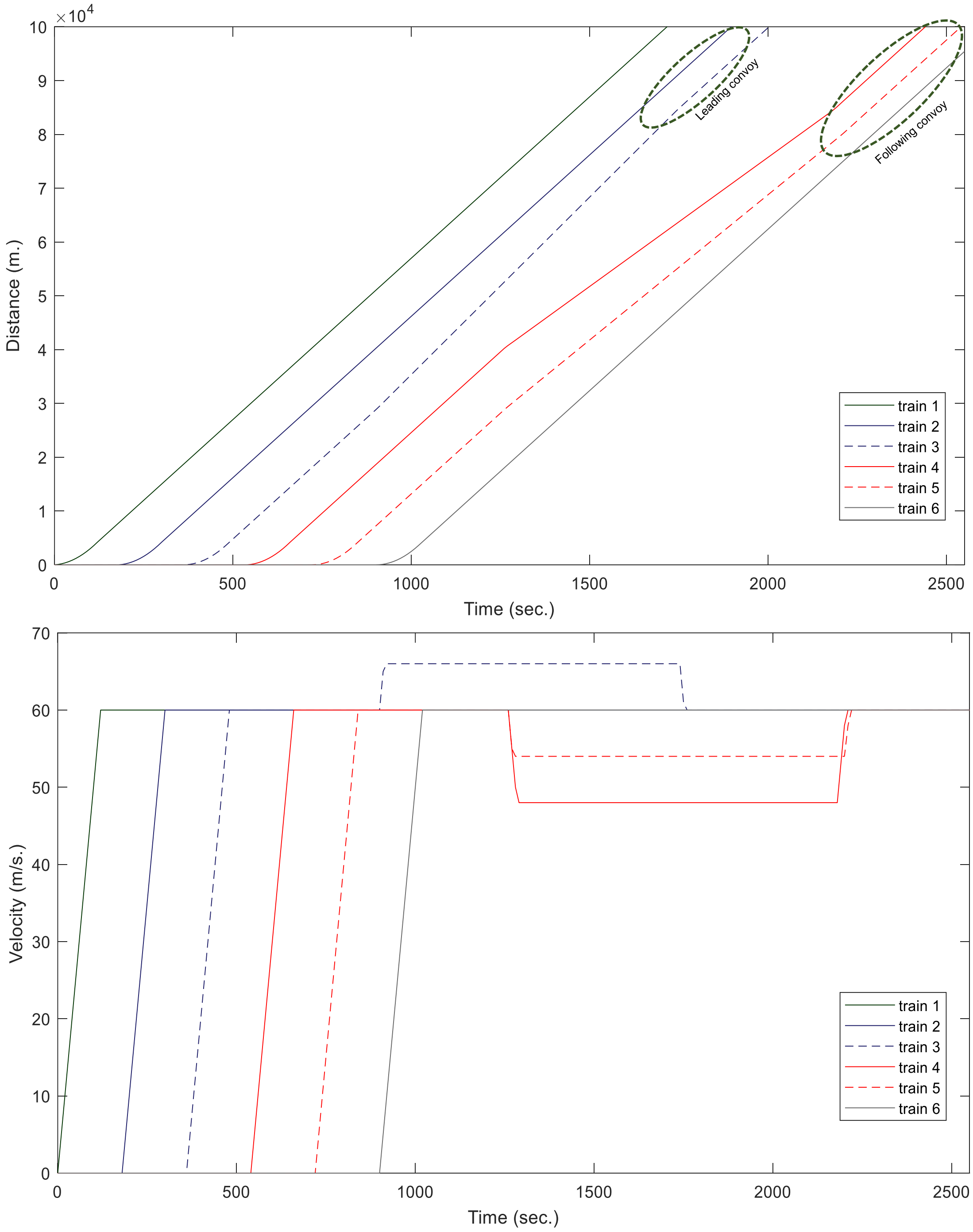


Figure 6.8 Simulated distance and velocity profile of trains in case 2

The simulated distance-time and velocity-time profiles of six trains on the route A are shown in **Figure 6.8**. It is seen that the train 3 accelerates from 60 m/s to 66 m/s for merged into the same convoy with the train 2 and then decelerate from 66 m/s to 60 m/s when entering the safe zone. It is obviously seen that the distance behind the leading convoy has been increased. The train 4 and train 5 decelerate to 48 m/s and 54 m/s respectively for merged into the same convoy with the train 6 for increasing in the time gap in front of the train 4.

The headway time between trains when passing the converging junction is illustrated in **Figure 6.9**. It is seen that, after building trains as the train convoys, the headway time between the train 3 and train 4 when passing the junction is increased from 180 sec to 440 sec. The headway time between the train 3 and the head of inserted convoy is increased from 120 sec to 190 sec. It is higher than the minimum permissible headway at 180 sec. Also, the headway time between the train m2 and the train 4 is increased from 60 sec to 190 sec which is high enough to pass the junction safely.

MBS

Train	Est. reaching time
m1	06:34:00
m2	06:35:00

Train	Est. reaching time
1	06:26:00
2	06:29:00
3	06:32:00
4	06:35:00
5	06:38:00
6	06:41:00

VCS

Train	Est. reaching time
m1	06:34:00
m2	06:35:10

Train	Est. reaching time
1	06:26:00
2	06:29:00
3	06:30:50
4	06:38:10
5	06:39:50
6	06:41:10

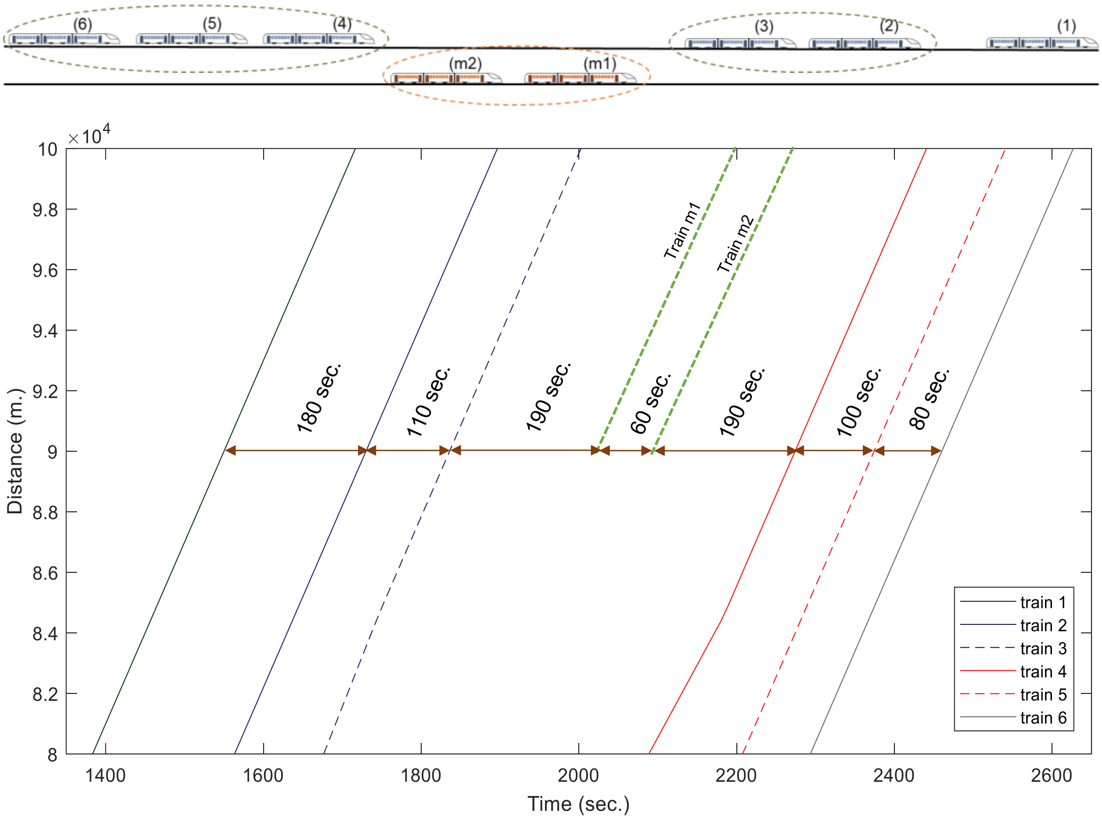


Figure 6.9 headway times between trains when passing converging junction: Case 2

6.5 Summary

In this part, the VCS is used to create a new train timetable by merging some trains together as a train convoy. The purpose is to increase the time gap between successive trains for inserting an extra train into the same route. The movement of trains based on a new timetable is simulated. According to the simulation results, it can be proved that the proposed approach can be applied to manage train timetable for increasing route capacity effectively. The time gap between trains after building some trains into a train convoy is high enough to insert an extra train safely. As a result, the route capacity in terms of the number of trains in an hour is increased compared to the maximum number of trains under the main signalling control (MBS).

Chapter 7
Applying the VCS to reduce delay: Applications used in operating state

7.1 Introduction

In peak-hour operation, the delay of one train could impact on many following trains operating on the same route. Some trains might be cancelled for recovering the timetable leading to a decrease in the route capacity and reliability. On the routes where capacity consumption is close to the maximum capacity, adding more trains into the same route might not be possible. Adding more services might impact badly on the train operation increasing the number of cancelled and delayed trains (ORR, 2020a). To increase route capacity, the VCS is applied for merging a group of trains as a train convoy to increase headway time for inserting more trains. The proposed approach and flowchart introduced in **Section 3.4** is used to create a new timetable, in which the number of trains that can operate along the same route is higher than the maximum umber of trains under the main signalling control. However, in operating state, the involved train (the train that will be built into a train convoy as stated in the planned timetable) may be delayed. The approach based on the VCS can be used to reduce delay by merging a delayed train and an impacted train operating behind into a train convoy.

The objectives and the methodology for evaluating the practical use of the VCS applications are explained in **Section 7.2** and **Section 7.3** respectively. There are four different applications used in different situations in operating state. The first situation is to use the VCS to reduce secondary delay when a train delay impacts the movement of its following trains (**Section 7.4.1**). The second situation that the VCS will be applied is when a train convoy approaches a junction (**Section 7.4.2**). As suggested in the planned timetable, some trains will be merged as a train convoy for extending the headway time to insert an extra train. In **Section 7.4.3**, the using of the VCS to build a train convoy according to the planned timetable is shown. The last situation in which the VCS will be applied is when any involved trains are already built into another convoy before start building a convoy according to the planned timetable (**Section 7.4.4**).

7.2 Objectives

In this chapter, the using of the VCS in operating state is determined. There are two main objectives including the increase of route capacity and the reduction of delay. To increase route capacity, the involved trains (as set in the timetable) will be built as a train convoy by using the optimal velocity as recommended in the planned timetable. They will be merged into a train convoy when reaching the merging point. The objective is to determine whether the VCS can be used to increase route capacity in terms of the number of trains that can operate along the same route. In the case that the involved train delay and cannot be merged into the train convoy using the optimal merging velocity as recommended in the timetable. The VCS application is used to redetermine a group of involved trains and re-calculate their optimal merging velocity. The objective is to determine the VCS ability to increase route capacity based on real-time data. Another objective is to control trains based on the VCS to reduce delay. The Objective is to reduce delay by merging a delayed trains and any impacted trains to operate as a train convoy.

7.3 Methodology

The VCS applications shown in **Section 3.5** is applied to determine the train operation under the VCS in operating state. In this chapter, the delay of trains when they procced under the MBS is compared to the delay when they operate under the VCS. Assuming that there are four situations in operating state. First, a train delays when it has operated along the route. Its delay impacts the movement of its following trains forcing them to decelerate causing delay as well. For this situation, the VCS application 1 shown in the **Section 3.5.1** is applied to merge a delayed train and an impacted train behind as a train convoy to reduce delay. Second, the VCS application 2 (**Section 3.5.2**) is applied to reduce delay when a train convoy passes a diverging junction. The delay time with and without the VCS is compared. Third, the route capacity in terms of the number of trains with and without the VCS is compared. Assuming that all involved trains operate on-time according to the planned timetable. In this case, the VCS application 3 (**Section 3.5.3**) is applied. Trains have operated under the VCS based on the proposed state movement in the **Section 3.2.1** and start merged into the convoy when reaching the merging point. Fourth, the VCS application 4 (**Section 3.5.4**) is applied in the case that an involved train (a train that will be merged into a train convoy as planned in the timetable) could not operate on-time. This VCS application is applied to re-determine the set of involved trains and to re-calculate the optimal merging velocity for a new involved train.

7.4 Test cases and simulation results

Four situations (four VCS applications) are simulated to determine the train operation under the VCS in operating state. Two situations in **Section 7.4.1** and **Section 7.4.2** are tested for determining whether the VCS can be used to reduce delay. The situations in **Section 7.4.3** and **Section 7.4.4** are simulated to determine whether the VCS can be applied to increase route capacity.

7.4.1 Applying the VCS application 1

Within 12 min defined time period, there are five trains departing from station A maintaining 3 min dispatching headway time. They will accelerate to 60 m/s and then operate by constant velocity approaching the converging junction that is placed at 90 km away from the station A (**Figure 7.1**). Assuming that the minimum headway time between trains under the MBS is 3 min. It means that the convoy proposal will be created and sent from the impacted train immediately when the headway time from the delayed train in front is lower than 3 min.

Train	Planned dispatching time	Arrival time
1	00:00:00	00:26:00
2	00:03:00	00:29:00
3	00:06:00	00:32:00
4	00:09:00	00:35:00
5	00:12:00	00:38:00

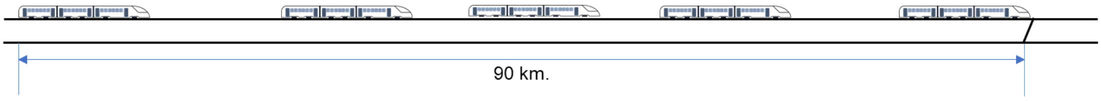


Figure 7.1 Test case: VCS application 1

Figure 7.2 shows the velocity-time and distance-time profiles of five trains when they operate under the MBS. It is seen that all trains have proceeded by the same velocity resulting the same travel time when they reach the junction. The movement of trains in three different test cases are simulated in order to determine whether the VCS could be used to reduce secondary delay.

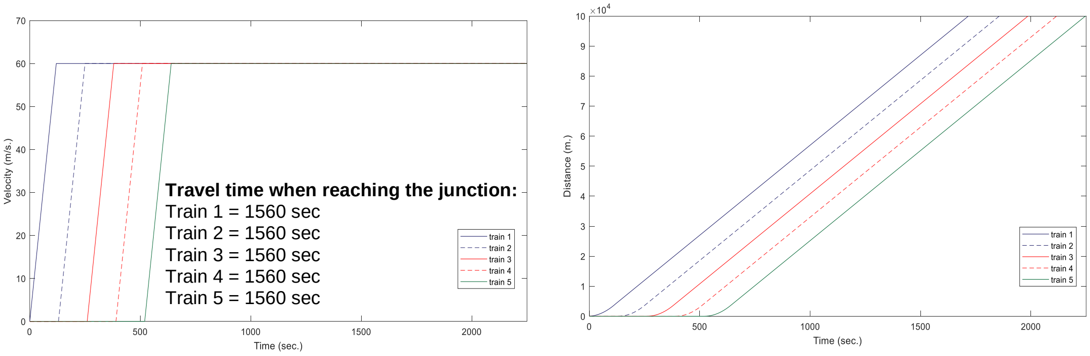


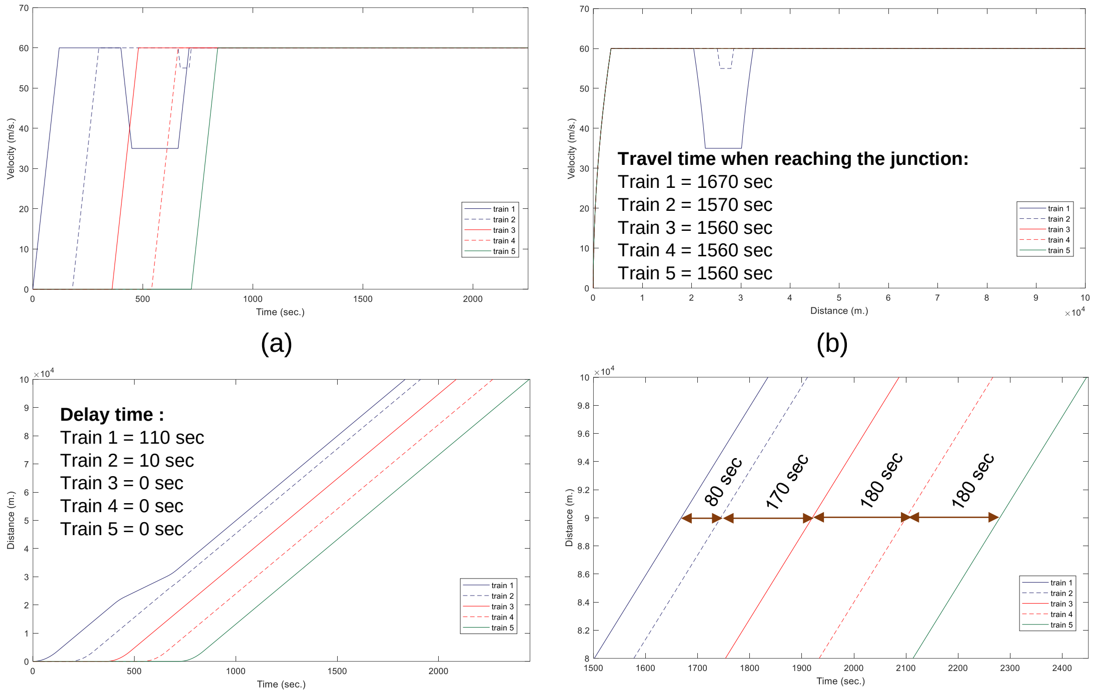
Figure 7.2 Simulated distance and velocity profile of trains under the MBS

Assuming that the train 1 decelerates from 60 m/s to 35 m/s and has proceeded by 35 m/s for 10 km, 30 km, and 50 km respectively causing different delays. The reduction in secondary delay of all following trains after applying the VCS application 1 in different test cases are shown below.

7.4.1.1 Proceeding by 35 m/s for 10 km

Assuming that the train 1 has operated by 35 m/s for 10 km causing 110 sec delay. **Figure 7.3** shows the distance and velocity profiles of five trains in the first test case. It is seen that the separation distance between train 1 and train 2 has been decreased due to the primary delay of the train 1 (**Figure 7.3 (c)**). Due to the deceleration of the distance between them, the optimal velocity of the train 2 in the next time step is normally lower than its ideal velocity. The train 2 will decelerate for maintaining safe distance separated from the train 1. The VCS application 1 is applied to reduce delay by building the delayed train 1 with the impacted train(s) proceeding behind into the same convoy. The convoy proposal is immediately created and sent from the train 2 to the train 1 requesting to be merged into the same convoy with the train 1. In this case, the train 1 accepts the convoy proposal because its velocity after receiving the convoy proposal is lower than the ideal velocity of the train 2, in which the distance between them has been decreased. Then, both trains will operate under the VCS based on the proposed approach in **Section 3.2.1**.

The movement authority of the train 2 has continuously been calculated based on the current position and velocity of the train 1. To build both trains together into the same convoy, the train 1 and train 2 have operated by 35 m/s and 60 m/s respectively. The minimum safe distance between them in the merging state is 5150 m. It means that the train 2 can operate by the ideal velocity at 60 m/s until the distance separated from the train 1 is shorter than 5150 m. According to the simulated velocity profile shown in the **Figure 7.3 (a)**, it is seen that the train 2 is forced to decelerate to 55 m/s in order to maintain safe distance separated from the train 1. Due to the deceleration of the train 2, the distance separated from the train 3 is reduced. As a result, the optimal velocity of the train 3 in the next time step is lower than its optimal velocity at 60 m/s. In this case, the VCS application 1 is applied to merge the train 3 with two trains in front into the same convoy. The train 3 is not forced to slow down and can operate by constant velocity because the distance separated from the train 2 is still longer than minimum safe distance under the VCS (**Figure 7.3 (d)**).



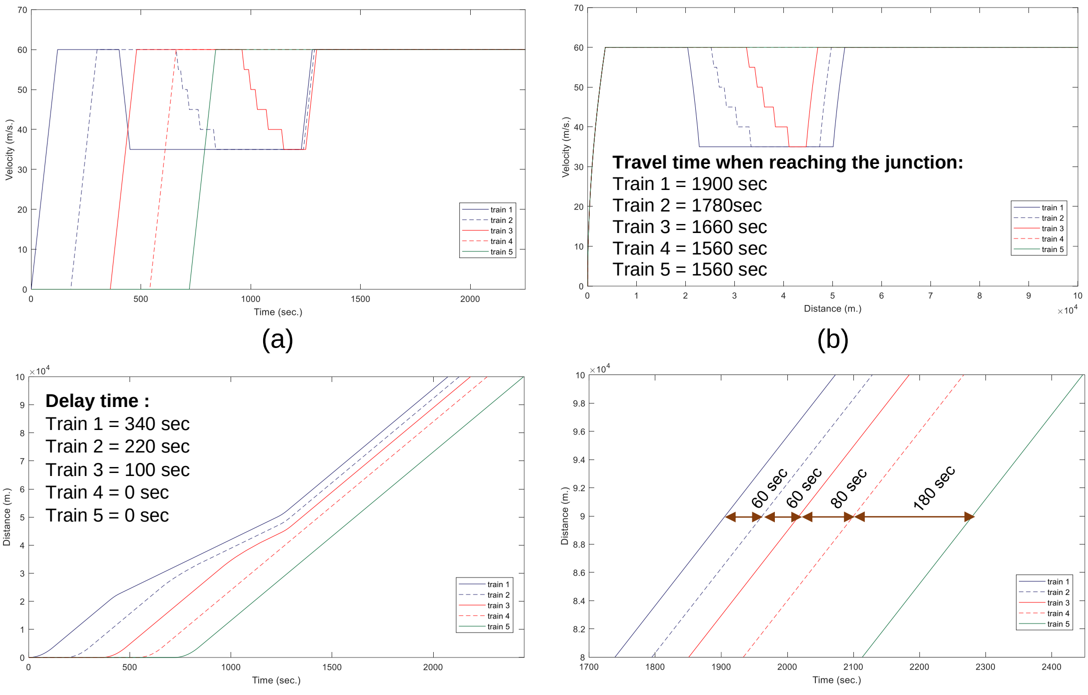
(a) (b) (c) (d)

Figure 7.3 Simulated distance and velocity profile: 110 sec primary delay

In this case, three trains including train 1, train 2, and train 3 are merged into the same convoy while the train 4 and train 5 have operated independently under the MBS. 110 sec delay of the train 1 has slightly impact on the train 2 causing delay for only 10 sec. In addition, it has no impact on the other trains proceeding behind.

7.4.1.2 Proceeding by 35 m/s for 30 km.

Assuming that the train 1 has proceeded by 35 m/s for 30 km causing delay for 340 sec. The distance separated from the train 2 has been decreased forcing the train 2 to decelerate to the same velocity as the train 1 (**Figure 7.4 (a)**). Coupling the train 2 into the same convoy with the train 1 could reduce delay of the train 2 for 120 sec (**Figure 7.4 (c)**). As seen in the **Figure 7.4 (b)**, the train 3 is forced to decelerate to the same velocity as its front trains as well. However, its delay is reduced by 240 sec compared to the train 1. Due to the delay of the train 3, the separation distance between the train 3 and the train 4 is decreased shorter than minimum safe distance under the MBS. In this case, the train 4 sends the convoy proposal requesting to join as the same convoy with three trains running in front. However, the train 4 could still operate by its ideal velocity without delay because the distance separated from the train 3 is still longer than minimum safe distance under the VCS.



(a) (b)

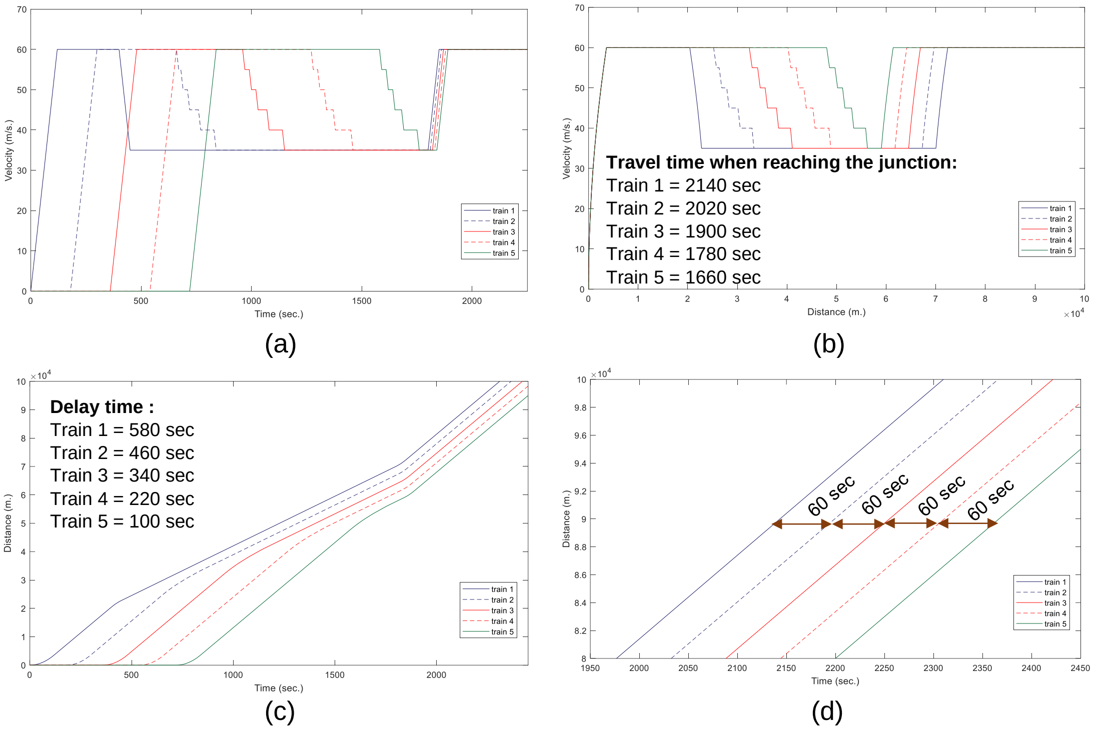
(c) (d)

Figure 7.4 Simulated distance and velocity profile: 340 sec primary delay

With 340 sec primary delay, four trains including train 1, train 2, train 3, and train 4 are merged into the same convoy to reduce secondary delay. Only the train 5 can operate independently under the MBS because there is no delay in the train 4 which will impact the movement of the train 5.

7.4.1.3 Proceeding by 35 m/s for 50 km.

For the last case, the first train has operated by 35 m/s for 50 km causing 580 sec primary delay. In this case, the delay of the train 1 affects the movement authority of all four trains proceeding behind **Figure 7.5 (a)**. They are merged into the same convoy and are stimulated to decelerate to the same velocity as the train 1. 580 sec delay of the train 1 impact the movement of all train causing delay in train 2, train 3, train 4, and train 5 for 460 sec, 340 sec, 220 sec, and 100 sec, respectively (**Figure 7.5 (c)**).



Travel time when reaching the junction:
Train 1 = 2140 sec
Train 2 = 2020 sec
Train 3 = 1900 sec
Train 4 = 1780 sec
Train 5 = 1660 sec

Delay time :
Train 1 = 580 sec
Train 2 = 460 sec
Train 3 = 340 sec
Train 4 = 220 sec
Train 5 = 100 sec

Figure 7.5 Simulated distance and velocity profile: 580 sec primary delay

In the last test case, all five trains are merged into the same train convoy for reducing secondary delay. Building them together into the same convoy could reduce secondary delay of the train 2, train 3, train 4, and train 5 by 120 sec, 240 sec, 360 sec, and 480 sec respectively.

7.4.1.4 Summary of the VCS application 1

When a train could not operate by its ideal velocity, the distance separated from its following train has been decreased affecting the movement of the following train forcing the following train to decelerate causing delay as well. To reduce secondary delay of a following train, the VCS application 1 is applied to merge the delayed train and all impacted trains together as a train convoy. An impacted train could operate by its ideal velocity until the distance separated from its front train is shorter than minimum safe distance under the VCS. According to the simulated results in three test cases above, it could be concluded that the VCS application 1 could be used to reduce secondary delay compared to the delay when trains operate under the MBS.

Figure 7.6 shows the delays of five trains in different primary delays. It is seen that the secondary delay of an impacted train is significantly decreased compared to the delay when trains operate under the MBS.

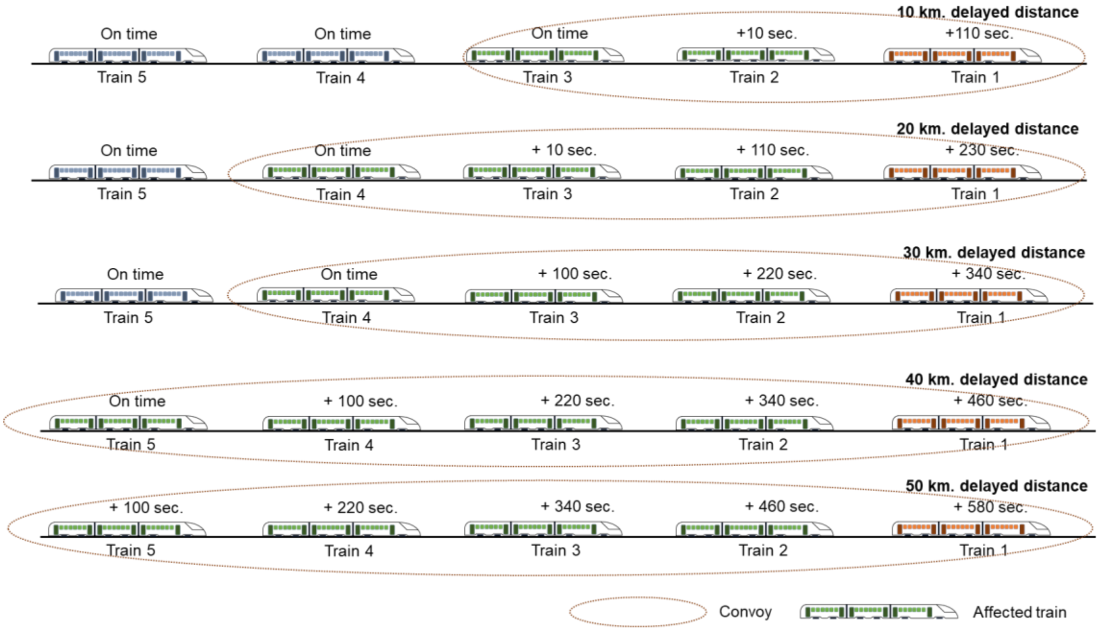
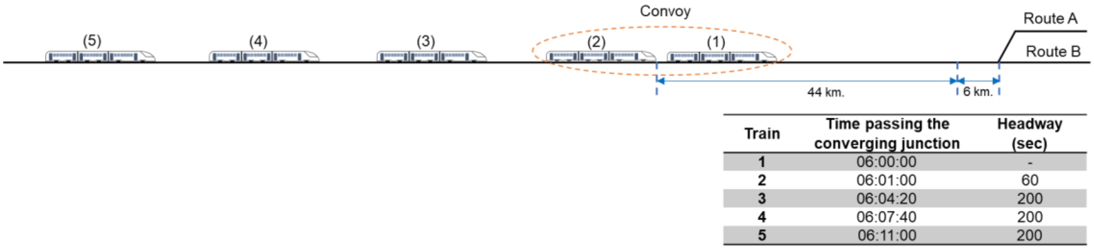


Figure 7.6 Delay after applying the VCS application 1

7.4.2 Applying the VCS Application 2

Within 15 min defined time period, there are five trains operating by the same velocity at 60 m/s approaching the diverging junction (**Figure 7.7**). Assuming that the train 1 and train 2 have proceeded as the same convoy while the train 3, train 4, and train 5 have operated independently under the MBS. The train 1 and train 2 will continue on the different routes after passing the junction requiring at least 210 sec headway time between them for passing through the junction. At least 180 sec is required for other couples of trains when successive trains continue on different routes, but only 120 sec headway time is required if successive trains continue on the same route.



Train	Time passing the converging junction	Headway (sec)
1	06:00:00	-
2	06:01:00	60
3	06:04:20	200
4	06:07:40	200
5	06:11:00	200

Figure 7.7 Test case: VCS Application 2

The train 2 starts splitting by decelerating from 60 m/s to 50 m/s when it reaches the splitting point set at 50 km away from the diverging junction. The deceleration of the train 2 for splitting causing delay for 150 sec will affect the movement of the trains proceeding behind differently depending on their routes. To evaluate the effectiveness of the VCS application 2, the secondary delay of the train 3, train 4, and train 5 after applying the VCS application 2 is compared to the delay when proceeding under the MBS. Three test cases are simulated as shown below.

7.4.2.1 Case 1: Train 2 and train 3 continue on the same route

Assuming that the delayed train 2 and the following train 3 will continue on the same route after passing the junction. The simulated velocity-time and distance-time profiles of five trains are shown in **Figure 7.8**. It is seen that the separation distance between train 1 and train 2 has been increased until it is higher than the minimum safe distance for passing the junction safely. As the train 2 and the train 3 continue on the same route after passing the junction, at least 120 sec headway time between them is required if they operate under the MBS (**Figure 7.9 (b)**). As a result, the train 3 will delay for 70 sec.

Applying the VCS application 2 could reduce delay in train 3. The delayed train 2 is merged into the same convoy with the impacted train 3. The headway time between them when passing through the junction is shown in **Figure 7.9 (a)**. It is seen that the headway time between train 1 and train 2 when passing the junction is increased to 210 sec while the headway time from the train 2 to the train 3 is decreased from 200 sec to 60 sec (minimum headway time under the VCS). As shown in **Figure 7.8 (left)**, the train 3 is forced to decelerate because the distance separated from the train 2 is shorter than minimum safe distance under the VCS with 10 m/s merging velocity difference (4125 m). It is not forced to decelerate to the same velocity as the train 2 because the distance between them is not shorter than minimum safe distance under the VCS with 5 m/s merging velocity difference.

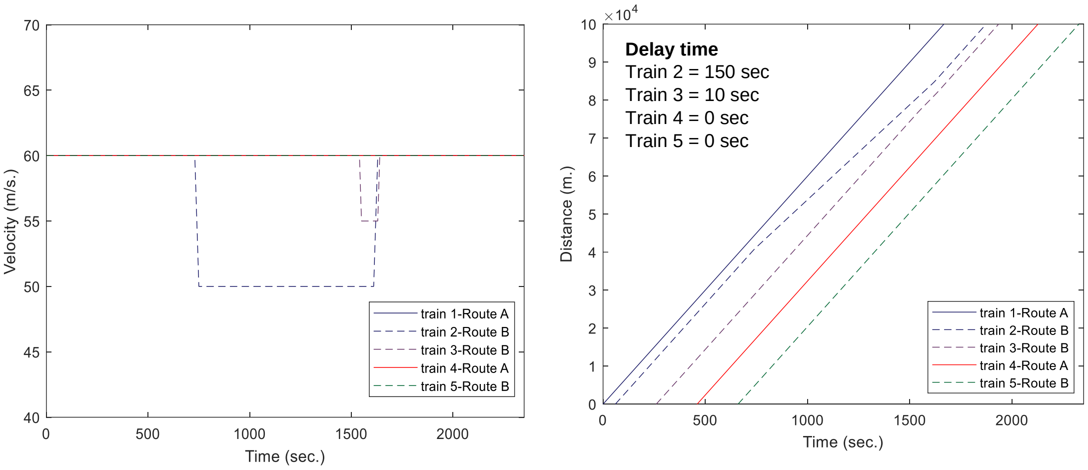
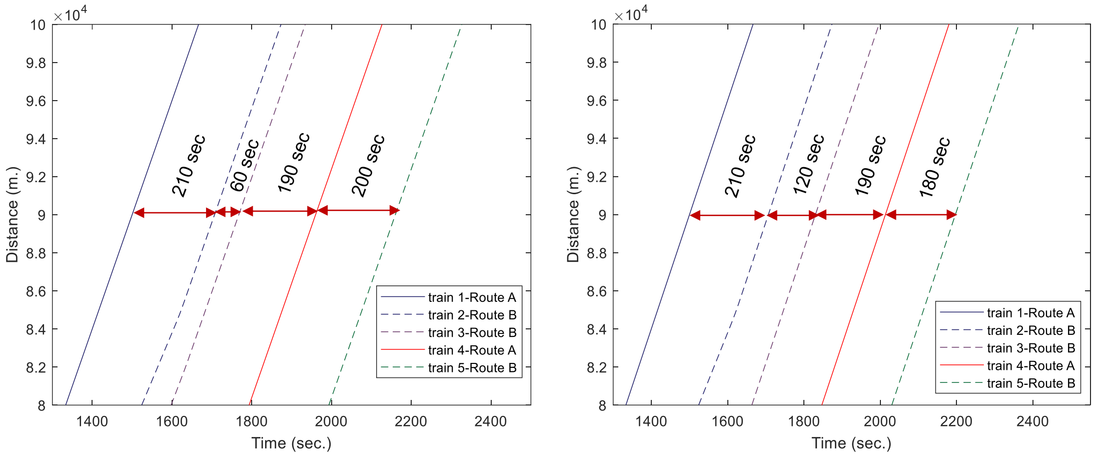


Figure 7.8 Building train 2 and train 3 as a train convoy

The headway time between train 3 and train 4 is decreased from 200 sec to 190 sec (**Figure 7.9 (b)**). It is still higher than minimum headway time required for passing the junction when successive trains continue on different route (at least 180 sec).



(a) VCS (b) MBS

Figure 7.9 The simulated distance-time profile: Case 1 (train 2 and 3 continue on the same route)

Table 7.1 shows the secondary delay of the train 3, train 4, and train 5 after applying the VCS application 2 compared to the delay under the MBS. If trains have operated under the MBS, the delay of the train 2 impacts the movement of all trains causing delay in all three trains operating behind. The delay for 150 sec of the train 2 causes 70 sec, 60 sec, and 40 sec, delay in the train 3, train 4, and train 5 respectively. If we apply the VCS application 2 to reduce secondary delay, there is only 10 sec delay in the train 3. The delay for 10 sec in the train 3 does not impacts the movement of the trains proceeding behind. There is no delay in train 4 and train 5 because the headway time from their front train is still higher than minimum headway time under the MBS.

Table 7.1 Secondary delay under MBS and VCS (Case 1: train 2 and train 3 continue on the same route)

Train	MBS		VCS	
	Passing junction	Delay (Sec)	Passing junction	Delay (Sec)
1	06:00:00		06:00:00	
2	06:03:30	150	06:03:30	150
3	06:05:30	70	06:04:30	10
4	06:08:40	60	06:07:40	0
5	06:11:40	40	06:11:00	0

7.4.2.2 Case 2: Train 3 and 4 continue on the same route

Similar to the first case, the train 2 has split out from its current convoy resulting delay for 150 sec. However, it could not be merged into the same convoy with its following train 3 because they will continue on different routes. Assuming that the train 3 and train 4 continue on the same route after passing the junction. Thus, it is possible to build the train 3 and train 4 together as a train convoy to reduce secondary delay in the train 3.

The simulated distance-time and velocity-time profile of five trains in this case are shown in **Figure 7.10**. It is seen that the separation distance between train 2 and train 3 has been decreased impacting the movement authority for the train 3. The train 3 is forced to decelerate earlier compared to the first test case because it needs to keep at least 180 sec away from the train 2. It decelerates to 50 m/s similar to the train 2 causing delay for 130 sec. Due to the deceleration of the train 3, the distance separated from the train 4 has been decreased affecting the movement authority of the train 4. Basically, if trains have operated under the MBS, the train 4 will be stimulated to decelerate as well when the headway time from the train 3 is lower than 120 sec. However, as the train 3 and train 4 continue on the same route after passing the junction, they could be merged into the same convoy for reducing secondary delay in the train 4.

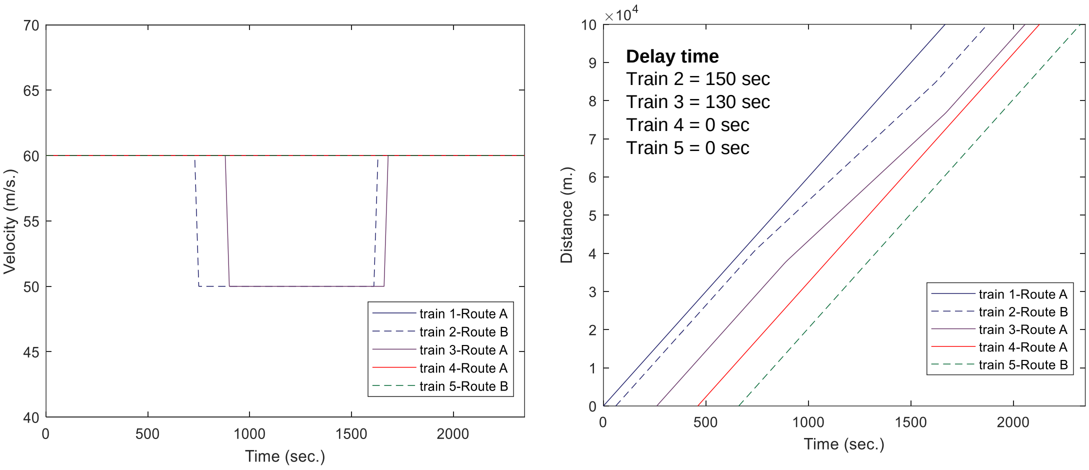
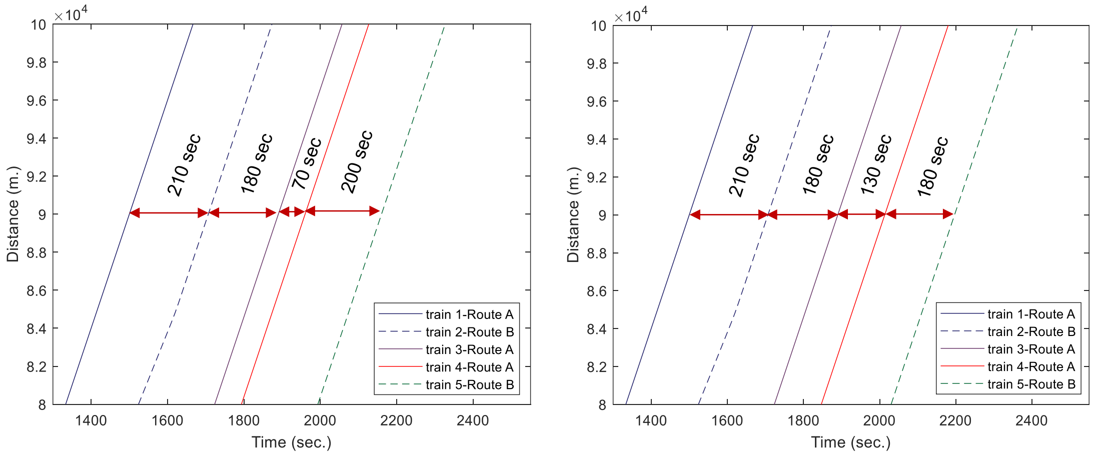


Figure 7.10 Building train 3 and train 4 as a train convoy

The simulated headway times between trains when passing through the junction is shown in **Figure 7.11**. After applying the VCS application 2 to control the train 4 to be merged into the same convoy with the train 3, the headway time between them is reduced to 70 sec. It is still higher than minimum headway time under the VCS (60 sec). Thus, the deceleration of the train 4's velocity does not impact the movement authority of the train 5 because the headway time between them is still higher than minimum headway time under the MBS. In this case, the train 5 could operate by the ideal velocity without delay.



(a) VCS (b) MBS

Figure 7.11 The simulated distance profile of trains when passing through the junction: Case 2, train 3 and 4 continue on the same route

The secondary delay of the trains after applying the VCS application 2 compared to the delay under the MBS are shown in **Table 7.2**. In both controls, the delay in the train 2 for 150 sec results 130 sec delay in the train 3. It causes the delay in the train 3, train 4, and train 5 for 130 sec, 60 sec, and 40 sec, respectively when they have operated under the MBS.

Table 7.2 Secondary delay under MBS and VCS (Case 2: train 3 and train 4 continue on the same route)

Train	MBS		VCS	
	Passing junction	**Delay (Sec)**	**Passing junction**	**Delay (Sec)**
1	06:00:00		06:00:00	
2	06:03:30	150	06:03:30	150
3	06:05:30	130	06:05:30	130
4	06:08:40	60	06:07:40	0
5	06:11:40	40	06:11:00	0

If the trains have operated under the VCS, successive train 3 and train 4 that will continue on the same route will be merged together as a train convoy. Thus, there is no delay in train 4 and train 5.

7.4.2.3 Case 3: Train 4 and 5 continue on the same route

Assuming that after passing the junction, the train 1 and train 3 will continue on the route A while the train 2, train 4, and train 5 will continue on the route B. As the decrease in the train 2's velocity, the distance separated from the train 3 has been shortened stimulating the train 3 to decelerate causing delay as well (**Figure 7.12**). The delay in train 3 for 130 sec impacts the movement authority of the train 4. As they continue on different routes, the train 4 is forced to decelerate as well for keeping at least 180 sec away from the train 3.

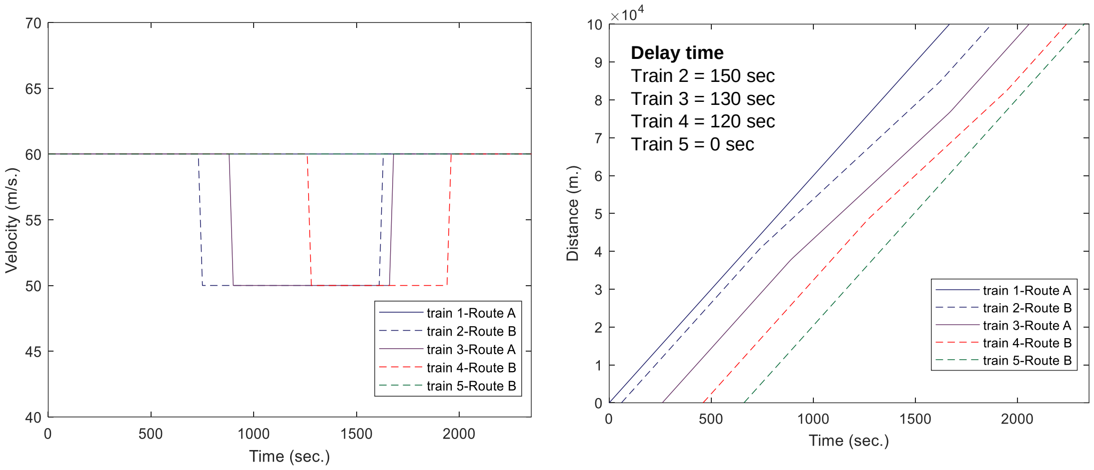
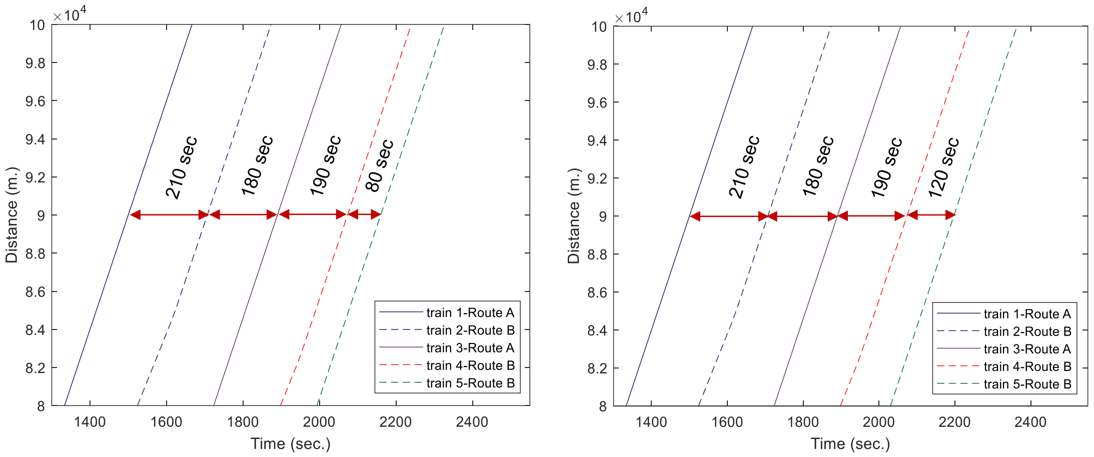


Figure 7.12 Building train 4 and train 5 as a train convoy

As the deceleration of the train 4, the distance separated from the train 5 has been decreased impacting the movement authority for the train 5. The train 5 is forced to decelerate when the headway time between from the train 4 is lower than 120 sec. If they have operated under the MBS, the delay in the train 4 causes delay in the train 5 for 40 sec. However, the train 5 could operate on time without delay when we apply the VCS application 2 to build train 4 and train 5 into the same convoy for passing the junction.



VCS MBS

Figure 7.13 The simulated distance profile of trains when passing through the junction: Case 3, train 4 and 5 continue on the same route

The simulated headway times between trains when passing through the junction is shown in **Figure 7.13** and the delay times of all trains in both controls are summarized in **Table 7.3**. It is seen that the headway time between train 4 and 5 after applying the VCS is decreased from 200 sec to 80 sec. It is still higher than the minimum headway time under the VCS required for passing the junction. Thus, by applying the VCS Application 2, the train 5 is not forced to decelerate and could be operate by its ideal velocity without delay.

Table 7.3 Secondary delay under MBS and VCS (Case 3: train 4 and train 5 continue on the same route)

Train	**MBS**		**VCS**	
	Passing junction	**Delay (Sec)**	**Passing junction**	**Delay (Sec)**
1	06:00:00		06:00:00	
2	06:03:30	150	06:03:30	150
3	06:05:30	130	06:05:30	130
4	06:08:40	60	06:08:40	60
5	06:11:40	40	06:11:40	0

7.4.2.4 Summary of the VCS application 2

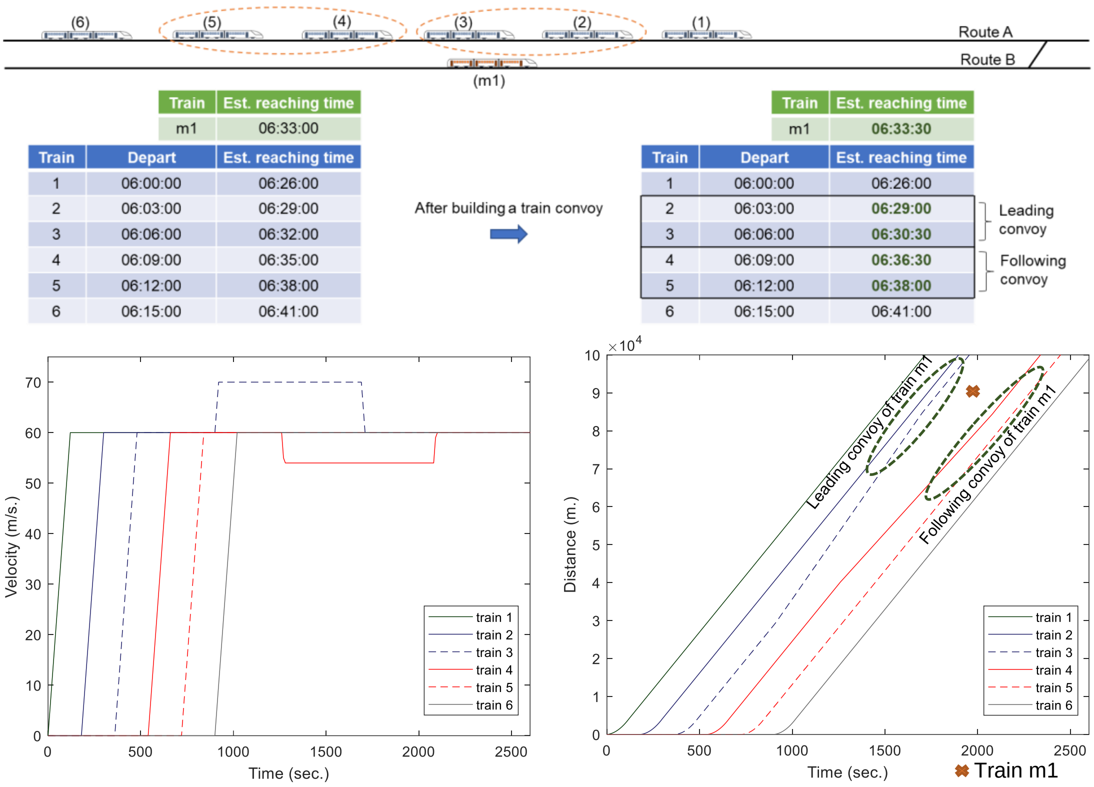
When a train convoy approaches a junction and any successive trains continue on the different routes, a following train will normally be forced to decelerate causing delay. Its delay may impact the trains proceeding behind forcing these trains to decelerate causing delay as well. To reduce secondary delay, the idea is to build the delayed train with the impacted train that will continue on the same route as a train convoy for passing through a junction as a single train. The simulated results in three test cases above shows that the secondary delay of trains when passing a junction could be reduced.

7.4.3 Applying the VCS application 3

The train operation based on the VCS Application 3 is shown in the test cases in **Section 6.4**. According to the simulated distance and velocity profile shown in **Figure 6.5**, it is seen that the simulated headway time between trains when passing a junction is not less than the minimum headway time for inserting an extra train.

7.4.4 Applying the VCS application 4

Assuming that there are six trains operating on the route A maintaining 3 min headway time between successive trains. They approach the converging junction, where train m1 from the route B will be inserted into the route A. Based on the planned timetable, train 2 and train 3 will be merged as the leading convoy while train 4 and train 5 will be built into the following convoy for lengthening the headway time to insert train m1. The velocity-time and distance-time profiles if trains have operated according to the planned timetable is shown in **Figure 7.14**. It is seen that the headway time between train 3 and train 4 has been increased from 180 sec to 360 sec which is high enough to insert the train m1 into the same route safely.



Train	Est. reaching time
m1	06:33:00

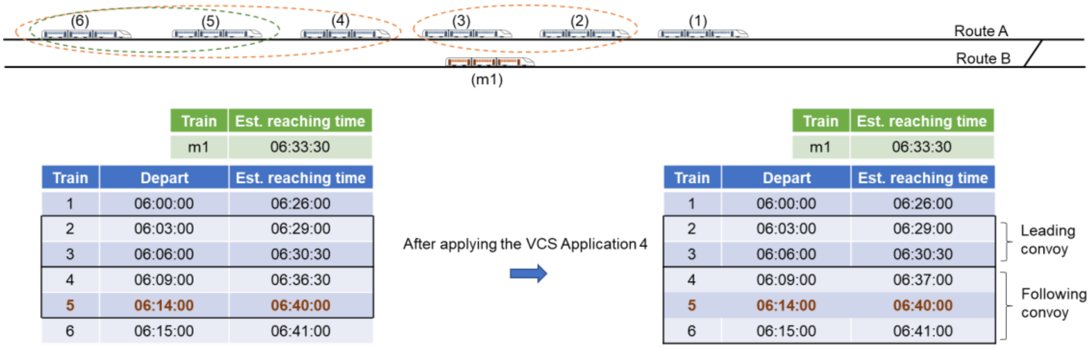
Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	06:29:00
3	06:06:00	06:32:00
4	06:09:00	06:35:00
5	06:12:00	06:38:00
6	06:15:00	06:41:00

Train	Est. reaching time
m1	**06:33:30**

Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	**06:29:00**
3	06:06:00	**06:30:30**
4	06:09:00	**06:36:30**
5	06:12:00	**06:38:00**
6	06:15:00	06:41:00

Figure 7.14 Building a train convoy based on the planned timetable

Assuming that the train 5 departs late by 2 min. It has been merged into the same convoy with the train 6 in order to recover the timetable. Thus, the estimated reaching time of the train 5 is changed. The estimated reaching time of all trains is shown in **Figure 7.15**. By comparing their estimated reaching time with the estimated time that the train m1, the sequence of trains passing through the junction is changed.



Train	Est. reaching time
m1	06:33:30

Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	06:29:00
3	06:06:00	06:30:30
4	06:09:00	06:36:30
5	**06:14:00**	**06:40:00**
6	06:15:00	06:41:00

Train	Est. reaching time
m1	06:33:30

Train	Depart	Est. reaching time
1	06:00:00	06:26:00
2	06:03:00	06:29:00
3	06:06:00	06:30:30
4	06:09:00	06:37:00
5	**06:14:00**	**06:40:00**
6	06:15:00	06:41:00

Figure 7.15 Example of using the VCS Application 4

Due to the change in estimated reaching time of the train 5, the VCS Application 4 will be applied for re-determining the set of involved trains and recalculating the optimal merging velocity of trains in the following convoy. For the leading convoy, the train 2 and train 3 which have operated on-time could be merged into the same convoy by using the optimal merging velocity as suggested in the planned timetable. The train 3 accelerates to 70 m/s for merged into the leading convoy with the train 2 which proceeds by constant velocity at 60 m/s. The headway time behind the leading convoy is increased for 90 sec.

The train 1 will reach the junction by 06:33:30. Thus, the headway time between train 3 (the last train in the leading convoy) and train m1 is 180 sec which is equal to the minimum headway time between trains required for passing through the junction safely. As the train 5 and train 6 are merged into the same convoy before reaching the merging point, they can be considered as a single train. They will be merged into the same convoy with the train 4. Thus, the train 4, train 5, and train 6 are built into the following convoy for increasing the headway time in front of the convoy.

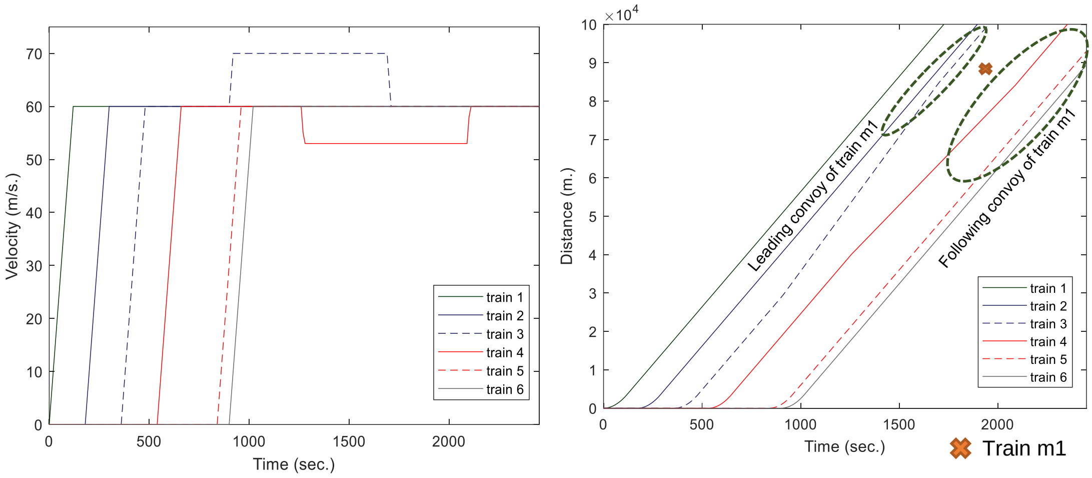


Figure 7.16 Simulated distance and velocity profile after applying the VCS Application 4

To insert the train m1 into the route A, the train 4, train 5 and train 6 will be built into the convoy by using **53 m/s, 60 m/s, and 60 m/s** merging velocity respectively. It is seen that the involved trains after applying the VCS Application 4 is different from the involved trains based on the planned timetable. According to the simulated velocity-time and distance-time profile of trains after applying the VCS Application 4 shown in **Figure 7.16**, it is seen that the headway time between train 3 and train 4 measured when passing the junction is 390 sec. It is higher than the minimum headway time required to insert the train m1. Thus, the train m1 could be inserted into the route A safely.

7.4.4.1 Summary of the VCS application 4

If trains that will be merged as a train convoy could not operate on-time and/or being built into another train convoy before reaching the merging point, the VCS Application 4 will be applied to redetermine an involved train and to recalculate the optimal merging velocity. As a result, the set of involved trains in each convoy and the optimal merging velocity might be changed. These are re-determined using the current information of trains when they approach the merging point. According to the simulated results of the test case, it is seen that the headway time between convoys is increased allowing any trains from other routes to be inserted into the same route safely.

7.5 Summary

This chapter shows the simulated results of the movement of trains following a new timetable (see more detail in the Chapter 6) and the simulated movement when trains delay. In the case that an involved train (a train that will be merged into a train convoy) delays, a group of involved trains is re-determined, and the merging velocity of an involved train is also re-calculated. According to the simulation result, it could be concluded that the VCS approach (VCS application 4) can be used to create a train convoy to increase route capacity. The headway time between convoys is high enough for inserting an extra train.

In the case of a train delay impacting the movement of its following train, the VCS (VCS application 1) could be used to reduce delay by merging a delayed train and an impacted train into a train convoy. According to the simulation result, it is found that the delay of an impacted train could be reduced compared to the delay when trains operate under the MBS. When a train convoy approaches a diverging junction, a following train is forced to decelerate to extend distance separated from its leading train. The deceleration of a train for splitting out from a train convoy may impact trains proceeding behind. The VCS application 2 will be applied to build trains that proceed on the same route into a train convoy to prevent delay. The simulation result shows that the delay could be reduced compared to the delay when trains operate under the MBS.

Chapter 8

Timetable planning and train operating under the VCS: A case study of high-speed train operating between East Midlands Hub and Yorkshire

8.1 Introduction

The HS2 is a new high-speed route operating between London and North of England serving more than 25 stations. There are 3 phases included in the project – Phase 1: the route between London and West midlands, Phase 2a: from West midlands to the North (via Crewe), and Phase 2b: from West midlands to Leeds and Manchester stations. The HS2 will provide major rail transportation connecting between cities across the UK. The main benefit from the project is to reduce travel time and increase route capacity serving an increasing in travelling demand. The network will operate with the high-speed trains running at approximately 360 km/h. Thus, approximately 18 trains could operate on the same route per one hour time period (HS2, 2021).

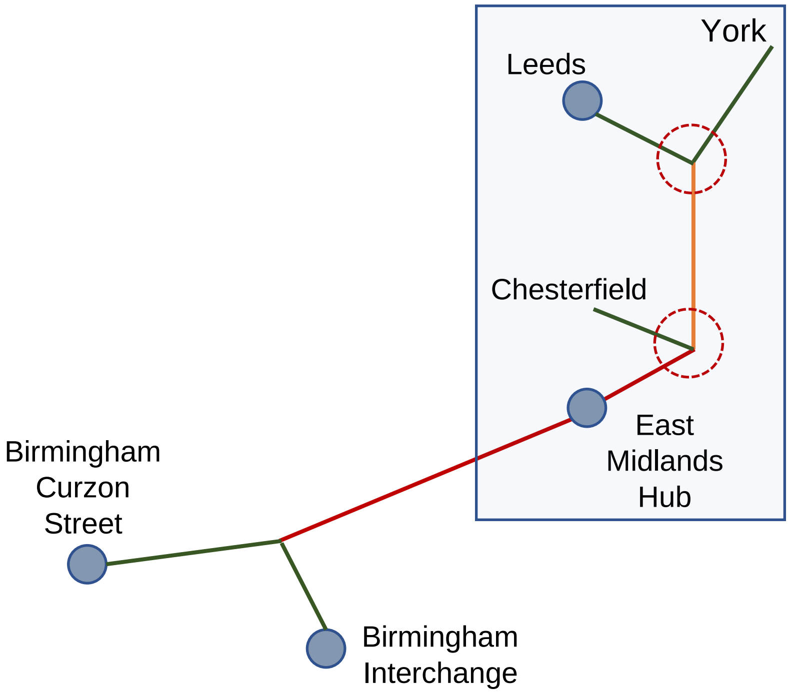


Figure 8.1 Route and stations between East-Midlands Hub and Yorkshire

In this study, the HS2 route between East Midlands Hub (EMH) and Yorkshire (a part of phase 2b) is selected as the case study (**Figure 8.1**). This is because if the operation between East Midlands Hub station and Yorkshire

(Main route) is nearly full, trains from Chesterfield could not be inserted into the main route. Inserting trains from Chesterfield into the main route might interrupt the operation of trains on the main route.

Figure 8.2 Section length and velocity limit (Department for transport, 2016)

The length and velocity limit of each section between EMH and Yorkshire are shown in **Figure 8.2** (Department for transport, 2016). A train from Yorkshire will operate by 60 m/s approaching the M62 junction. It will accelerate to 100 m/s after passing M62. Then, it will decelerate to 60 m/s for passing through the M1 junction.

Table 8.1 Operational parameters of HS2

Parameters		
1) Velocity limit between Yorkshire route and M62	60	m/s
2) Velocity limit between M62 and M1 junction	100	m/s
3) Velocity limit between M1 junction and EMH station	60	m/s
4) Turnout velocity limit (v^{maxp})	30	m/s
5) Time step (Δt)	10	sec
6) Safety margin time (SMt), (See more detail in **Section 2.2**)	58	sec
7) Maximum acceleration rate (a^{max})	0.5	m/s^2
8) Maximum deceleration rate (b^{max})	0.5	m/s^2
9) Turnout junction operation time (T^{pnt})	12	sec
10) Station spacing (z^{total}) from Leeds to East midland hub	106.2	km
11) Distance between M62 and M1 junction	75.2	km
12) Train length (l) (trains on the main route)	400	m
13) Inserted train length (l_m) (trains operating from Chesterfield)	400	m

8.2 Objectives

It is well known that the VCS could be applied to reduce the headway time between successive trains that could increase the percentage of unused capacity. The number of trains that can operate on the same route within defined time period is possibly higher than the maximum number of trains under other controls. However, the problem is how can we manage timetable and add more trains into the system, and how can we reduce delay.

The objective of this chapter is to use the proposed approaches and VCS applications from the previous chapters applying on the HS2 operation for determining to possibility to run more trains on the same route.

8.2.1 Creating a new timetable

In the case that the number of trains that will operate on the same route exceeds the available capacity under the main control, the VCS approach in **Section 3.4** will be used to create a timetable. Some trains will be merged as a train convoy to increase the time gap for inserting an extra train. The planner can use this proposed approach to determine which trains should be built as a train convoy, the number of trains in each convoy, when trains should start merged into a convoy, and the optimal merging velocity that trains should operate for merged into a train convoy.

8.2.2 Increasing capacity, maintaining safety and improving stable travelling

In operating state, the involved trains will start built into a train convoy by adjusting their velocity as suggested in the planned timetable. Then, they will operate based on the proposed approach shown in **Section 3.2.2**. By following the proposed approach, it is ensured that trains can operate safely and obtain stable travelling.

8.2.3 Reducing secondary delay

In the case that a train could not operate on-time causing delay affecting the movement of the trains running behind, the VCS applications in **Section 3.5.1 is** applied. A delayed train will be merged with the impacted trains as a train convoy for reducing delay. In the case that any successive trains continue on different routes after passing a junction, a following train might be forced to decelerate affecting the movement authority of trains running behind. It will be merged as a train convoy with its impacted following train in order to reduce delay if they will proceed on the same route. The approach introduced in **Section 3.5.2** is applied to create a train convoy passing through a diverging junction.

8.3 Methodology

The route capacity and delay of trains after applying the VCS application are compared to the capacity and delay when trains operate under the MBS (main signaling control). The minimum headway time required for the MBS is described in **Section 8.3.1**. The simulated distance-time and velocity-time profile of trains under MBS are shown in **Section 8.3.2**. Assuming that the number of trains that will operate between EMH and Yorkshire is equal to the maximum number of trains that could operate under the MBS. But there are extra trains from Chesterfield that will be inserted into the main route. They will interrupt the movement of trains in the main route.

The proposed VCS approach and flowchart in **Section 3.4** are used to create the timetable according to the number of trains that will operate along the same route (**Section 8.4**). Assuming that five trains from Chesterfield route will be inserted into the main route via M1 junction. The train timetables in both directions (from EMH to Yorkshire, and from Yorkshire to EMH) are created. The involved trains in each train convoy and their optimal merging velocity are calculated and set as a guideline used in operating state. In operating state, train movement in two situations is considered.

For the first test case (**Section 8.5**), assuming that all trains within the defined time period have operated on time. The **VCS Application 3 (Section 3.5.3)** will be applied to control the involved trains coupled into train convoys. The **VCS Application 3 (Section 3.5.3)** will be applied to control the involved trains coupled into train convoys. They will operate in relation to the information set in the planned timetable. When passing through the junction, a following train in a convoy may decelerate for lengthening the distance separated from its front train. The **VCS Application 2 (Section 3.5.2)** will be applied when trains have passed through the junction to reduce delay. The **VCS Application 2 (Section 3.5.2)** will be applied when trains have passed through the junction to reduce delay.

For the second test case (**Section 8.6**), assuming that some trains delay before start merged into a convoy. In this case, the **VCS Application 1** (**Section 3.5.1**) will be used to reduce secondary delay by merging a delayed train and any impacted trains together as a train convoy. In this case, the **VCS Application 1** (**Section 3.5.1**) will be used to reduce secondary delay by merging a delayed train and any impacted trains together as a train convoy. Then, when trains are approaching the M1 junction, a set of involved trains and the optimal merging velocity of the updated involved trains are recalculated by using the **VCS Application 4** (**Section 3.5.4**). Then, the VCS

Application 2 **(Section 3.5.2)** will be applied to reduce delay when trains have passed through the M62 junction.

8.3.1 Minimum headway time under the MBS

The trains on the main route could pass through the M1 junction by 100 m/s while the trains from Chesterfield will need to slow down and pass the junction by 60 m/s at maximum. The total time that a train from Chesterfield has passed through the junction by its whole length is approximately 7 sec. Then, the turnout will be moved back for the next train using 12 sec operation time. At the same time period (19 sec), a train on the main route still operate by 100 m/s covering 1900 m while the distance covered by a train from Chesterfield is 1140 m. The minimum safe distance required for passing the M1 has to be extended by 760 m. Thus, the minimum safe distance between trains at the M1 junction is

$$\Delta x_1^{mcvr} = \left(\frac{(v^{max})^2}{2b_2^{max}} + SM\right) + (T^{pnt}v^{max}) + l_1 + \Delta x_m^{cvr}$$

$$\Delta x_1^{mdvr} = \left(\frac{(60)^2}{2(0.5)} + (58 \times 60)\right) + (12 \times 60) + 400 + 760 = 8960\ \mathrm{m}.$$

The absolute braking time required for passing through the M1 junction safely is approximately 150 sec. According to the recommendation by UIC 406, the maximum number of trains per hour should not be more than 75% of maximum number of trains at the worst-case situation. Thus, the maximum number of trains under the main control in one-hour operation time period should not be more than (3600/150) x 0.75 = 18 trains. Thus, the maximum permissible headway time under the MBS is 200 sec.

8.3.2 Trains operation under the MBS

Based on the track layout in **Figure 8.2** and operational parameters in **Table 8.1**, the ideal velocity profiles of a train operating under the MBS in both legs are shown in **Figure 8.3** and **Figure 8.5**.

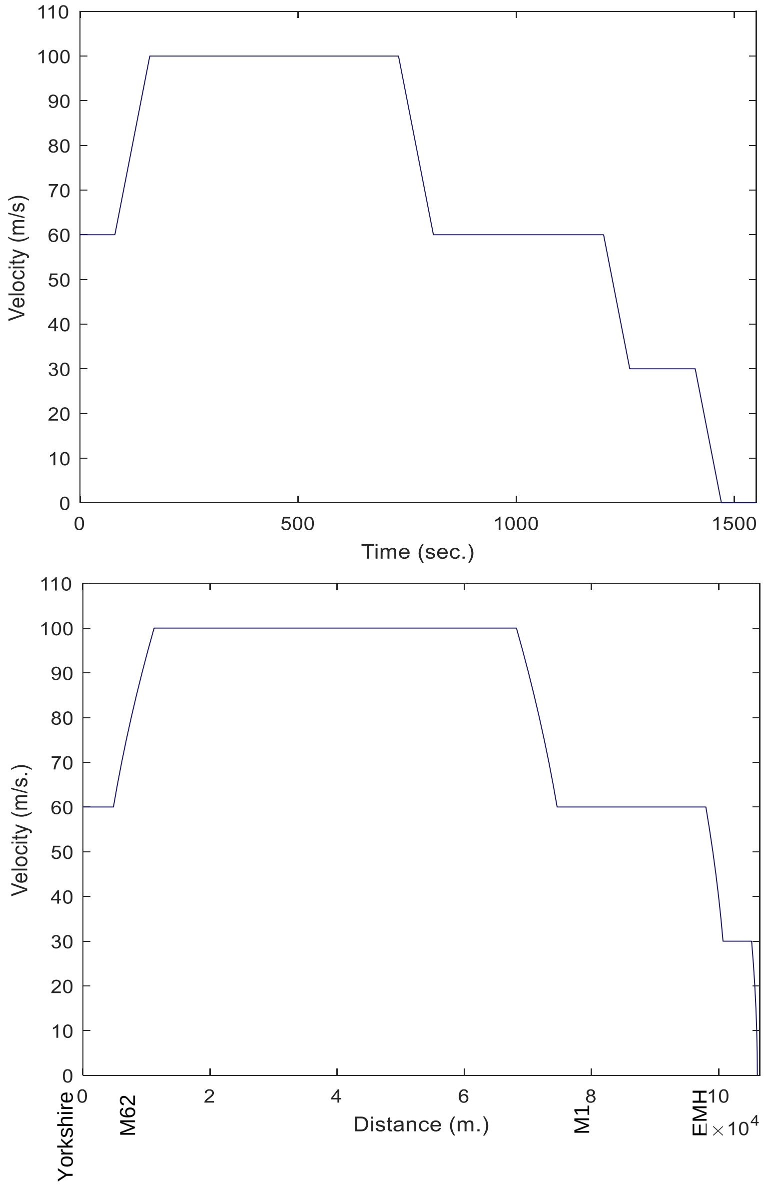


Figure 8.3 Ideal velocity profile: from Yorkshire to EMH

From Yorkshire (Leeds and York stations) to EMH, trains which depart from Leeds and York stations will operate by 60 m/s before passing the M62 junction. After passing the M62 junction, they will accelerate to the top velocity at 100 m/s and then proceed by 100 m/s approaching the M1 junction. Then, they will decelerate from 100 m/s to 60 m/s for passing through the M1 junction. Assuming that 18 trains (9 trains from Leeds station, and 8 trains from York station) have proceeded from Yorkshire to EMH covering 100% of route capacity. **Figure 8.4** shows the distance-time profile of 18 trains operating under the MBS.

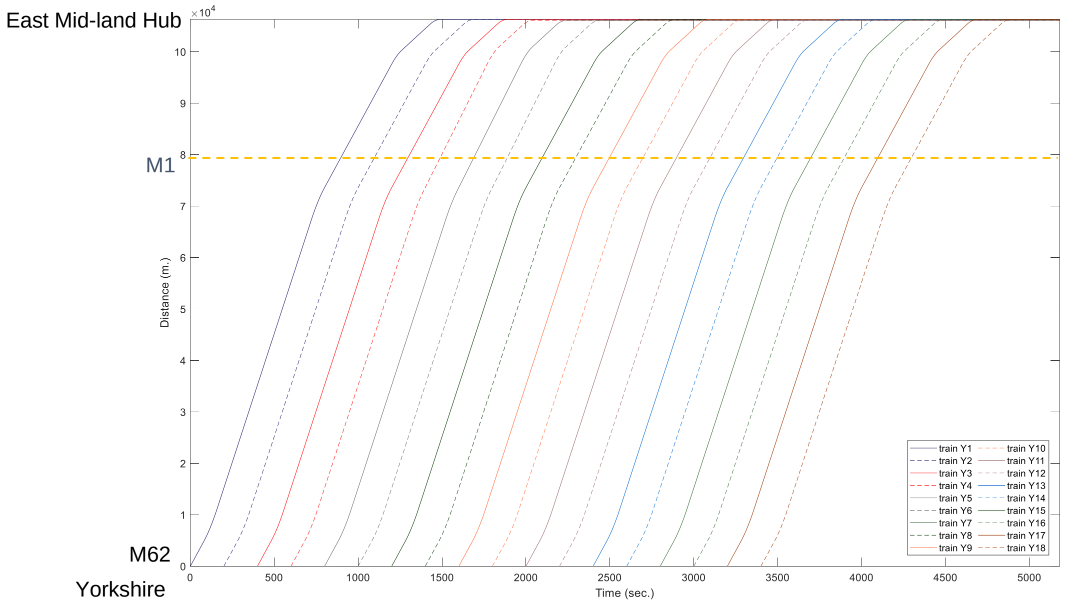


Figure 8.4 Simulated distance-time profiles of trains under the MBS: from Yorkshire to EMH

Figure 8.5 shows the ideal velocity profile of a train operating from EMH station to Yorkshire. The trains will accelerate to 30 m/s and then proceed by constant velocity for passing through the turnout set at 3.6 km away from EMH station. After passing the turnout, they will accelerate again to 60 m/s passing through M1 junction. After that, they will speed up again from 60 m/s to 100 m/s to proceed through the route section between M1 and M62. Then, they will decelerate to 60 m/s for passing M62 junction and then proceed by 60 m/s continuing to either Leeds or York stations. In one hour defined time period, 18 trains will depart from EMH station maintaining 200 sec headway time.

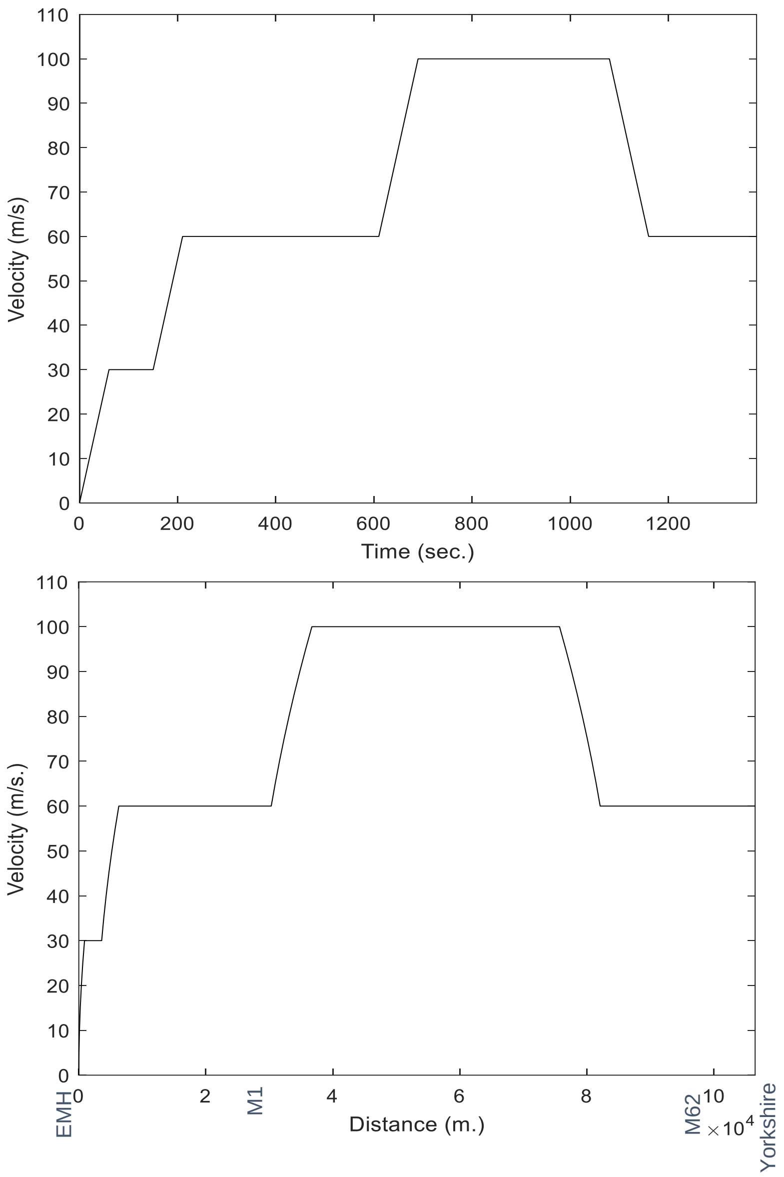


Figure 8.5 Ideal velocity-distance profile: from EMH to Yorkshire

8.4 Creating a timetable

The proposed approach and flowchart in **Section 3.4** are used to determine which and how many trains should be merged into a train convoy, and to calculate the optimal velocity that a train has operated for merged into a train convoy. The bidirectional leader communication type is selected as the communication system. The trains could send and receive the information between them. In addition, the First train can send information to all involved trains proceeding behind. In this case study, the timetables in 1 peak-hour operation in both directions are created. 23 trains (18 trains on the main route and 5 trains from Chesterfield) will operate along the route between M1 junction and EMH station.

8.4.1 From Yorkshire to East Midland Hub

Assuming that 18 trains depart from Yorkshire (from both Leeds and York stations) passing the M1 junction at the time shown in **Table 8.2**. Five trains, train CE1, CE2, CE3, CE4, and CE5 from the Chesterfield route will be inserted into the main route via M1 junction. Based on their ideal velocity profile, they will arrive at M1 junction at 07:21:00, 07:37:00, 07:53:00, 07:54:40, and 08:11:00 respectively.

Table 8.2 Original timetable for trains from Yorkshire to East Midland Hub

Train	Origin	Passing M1	Train	Origin	Passing M1
Y1	York	07:15:00	Y10	Leeds	07:45:00
Y2	Leeds	07:18:20	Y11	York	07:48:20
Y3	York	07:21:40	Y12	Leeds	07:51:40
Y4	Leeds	07:25:00	Y13	York	07:55:00
Y5	York	07:28:20	Y14	Leeds	07:58:20
Y6	Leeds	07:31:40	Y15	York	08:01:40
Y7	York	07:35:00	Y16	Leeds	08:05:00
Y8	Leeds	07:38:20	Y17	York	08:08:20
Y9	York	07:41:40	Y18	Leeds	08:11:40

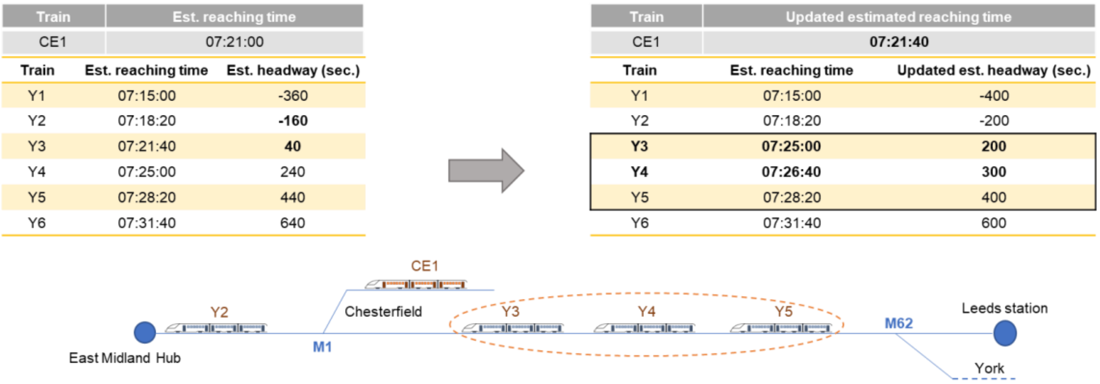
8.4.1.1 Inserting the train CE1

According to the original timetable shown in **Table 8.2**, the train CE1 will reach the M1 junction at 07:21:00 and will be inserted into the main route between the train Y2 and train Y3. The estimated headway time between the train CE1 and its front train (train Y2) when passing the M1 junction is 160 sec. Thus, at least 40 sec extra headway time behind the train Y2 is required to insert the train CE1 safely. However, due to velocity limit along this route section, the leading convoy could not be built because the following train in the leading convoy could not accelerate to velocity higher than 100 m/s. Thus, the time gap in front of the train CE1 could not be extended. In this case, the train CE1 should slow down for maintaining safe headway time from the train Y2. Its estimated reaching time at the M1 junction is updated and changed from 07:21:00 to 07:21:40.

According to the updated headway time between the train CE1 and its involved trains shown in **Figure 8.6**, it is seen that the headway time from the inserted train CE1 and Y3 and Y4 is not safe (shorter than the minimum headway time). Thus, the train Y3 and train Y4 should be merged into the same convoy with the train Y5 (reference train) for extending time gap in front of the train Y3. At least 200 sec extra headway time in front of the train Y3 required. If the involved trains start merged into the same convoy after passing M62 junction and will stop merged before decelerating to pass the M1 junction, the merging distance is 61.72 km. **Equation (3-57)** is used to calculate the optimal merging velocity for the first train in a following convoy. The optimal merging velocity of the train Y3 is

$$v_{Y3}^{mer} = v_{Y5}^{mer} \Big/ \left(1 + \left(\frac{\Delta x_{Y3}^{ext}}{\Delta x^{mer}}\right)\right) = 100 \Big/ \left(1 + \left(\frac{20000}{61720}\right)\right) = 76 \text{ m/s}$$

and the optimal merging velocity for the train Y4 (**Equation (3-50)**) is 76+12 = 88 m/s.



Train	Est. reaching time	
CE1	07:21:00	
Train	**Est. reaching time**	**Est. headway (sec.)**
Y1	07:15:00	-360
Y2	07:18:20	**-160**
Y3	07:21:40	**40**
Y4	07:25:00	240
Y5	07:28:20	440
Y6	07:31:40	640

Train	Updated estimated reaching time	
CE1	**07:21:40**	
Train	**Est. reaching time**	**Updated est. headway (sec.)**
Y1	07:15:00	-400
Y2	07:18:20	-200
Y3	**07:25:00**	**200**
Y4	**07:26:40**	**300**
Y5	07:28:20	400
Y6	07:31:40	600

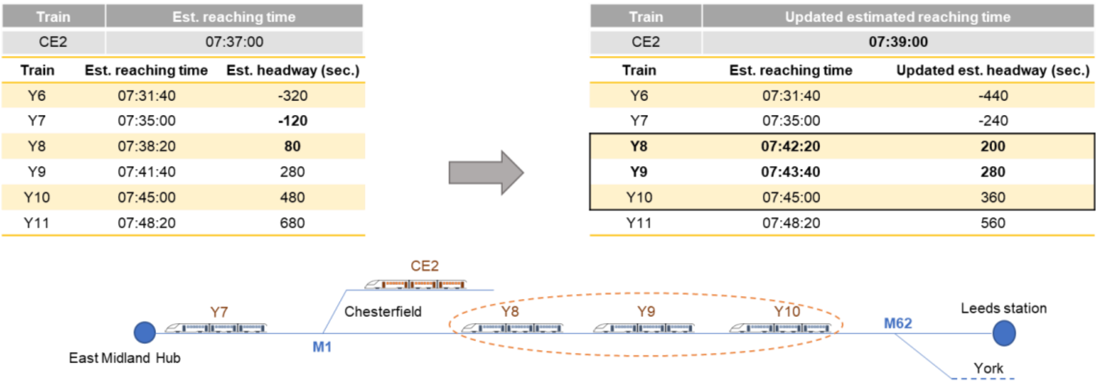
Figure 8.6 Estimated headway time between train CE1 and the involved trains

Thus, the train Y3, Y4, and Y5 will be merged into the same convoy by using 76 m/s, 88 m/s, 100 m/s merging velocity respectively.

8.4.1.2 Inserting the train CE2

Assuming that the train CE2 has a lower braking capability than the other trains running on the main route. At least 240 sec headway time in front of the train CE2 is required due to its lower braking rate. By comparing the estimated reaching time, the train CE2 will be inserted into the main route between the train Y7 and Y8 by the estimated time shown in **Figure 8.7**. The headway time between the train Y7 and CE2 is only 120 sec lowering than the minimum headway time at 240 sec. Thus, at least 120 sec extra headway time between them is required. However, the time gap in front the inserted train CE2 could not be extended due to the velocity limit restricted along the route section between M62 junction and M1 junction. In this case, the inserted train CE2 should reach the M1 junction by 07:39:00 in order to keep the safe headway time away from the train Y7.

The headway times from the inserted train CE2 and its involved trains are updated as shown in **Figure 8.7**. It is seen that the headway time from the train CE2 to both train Y8 and Y9 is lower than the minimum headway time at 200 sec.



Train	Est. reaching time	
CE2	07:37:00	
Train	**Est. reaching time**	**Est. headway (sec.)**
Y6	07:31:40	-320
Y7	07:35:00	**-120**
Y8	07:38:20	**80**
Y9	07:41:40	280
Y10	07:45:00	480
Y11	07:48:20	680

Train	Updated estimated reaching time	
CE2	**07:39:00**	
Train	**Est. reaching time**	**Updated est. headway (sec.)**
Y6	07:31:40	-440
Y7	07:35:00	-240
Y8	**07:42:20**	**200**
Y9	**07:43:40**	**280**
Y10	07:45:00	360
Y11	07:48:20	560

Figure 8.7 Estimated headway time between train CE2 and the involved trains

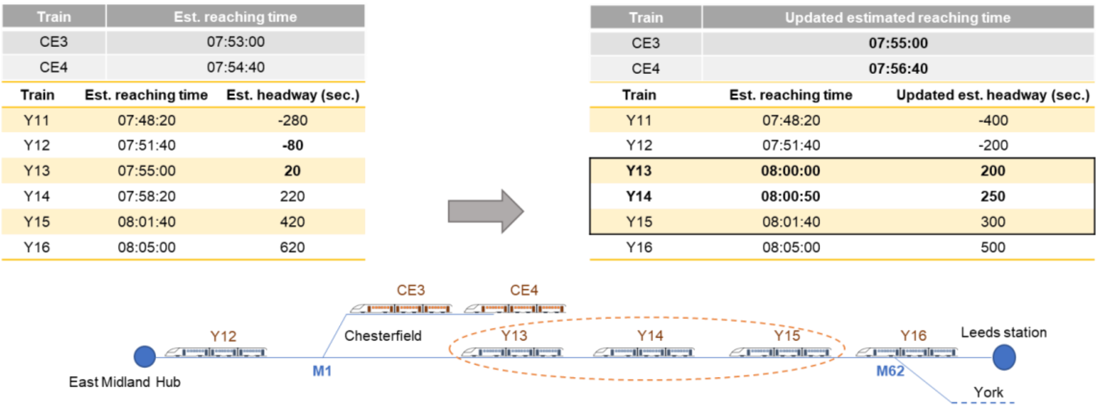
Thus, both trains should be merged as a train convoy with the reference train Y10 in order to extend the time gap in front of the train Y8. The extra time gap needed in front of the following convoy is |-120|+120 = 240 sec requiring the train Y8 being merged into a train convoy by

$$\mathrm{v}_{\mathrm{Y8}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{Y10}}^{\mathrm{mer}} \Big/ \left(1+\left(\frac{\Delta \mathrm{x}_{\mathrm{Y8}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 100 \Big/ \left(1+\left(\frac{24000}{61720}\right)\right) = 72\ \mathrm{m/s}$$

The train Y9 (middle train in this train convoy) will be merged into the convoy by 72+14 = 86 m/s. In this case, the train Y8, train Y9, and train Y10 will be merged into the same convoy by using 72 m/s, 86 m/s, and 100 m/s merging velocity respectively.

8.4.1.3 Inserting the train CE3 and train CE4

Assuming that the train CE3 and train CE4 have operated as the train convoy maintaining 100 sec headway time approaching the M1 junction. They will reach the junction at 07:53:00 and 07:54:40 respectively. By comparing the estimated reaching time to the trains on the main route, this convoy will be inserted into the main route between the train Y12 and train Y13. At least 200 min headway time between train Y12 and the train CE3 (the first train in the inserted convoy) is required. However, the estimated headway time between them is only 80 sec. Thus, at least 120 sec extra headway time is required in front of the following convoy.



Train	Est. reaching time
CE3	07:53:00
CE4	07:54:40

Train	Est. reaching time	Est. headway (sec.)
Y11	07:48:20	-280
Y12	07:51:40	**-80**
Y13	07:55:00	**20**
Y14	07:58:20	220
Y15	08:01:40	420
Y16	08:05:00	620

Train	Updated estimated reaching time
CE3	**07:55:00**
CE4	**07:56:40**

Train	Est. reaching time	Updated est. headway (sec.)
Y11	07:48:20	-400
Y12	07:51:40	-200
Y13	**08:00:00**	**200**
Y14	**08:00:50**	**250**
Y15	08:01:40	300
Y16	08:05:00	500

Figure 8.8 Estimated headway time between a train convoy (CE3 and CE4) and the involved trains

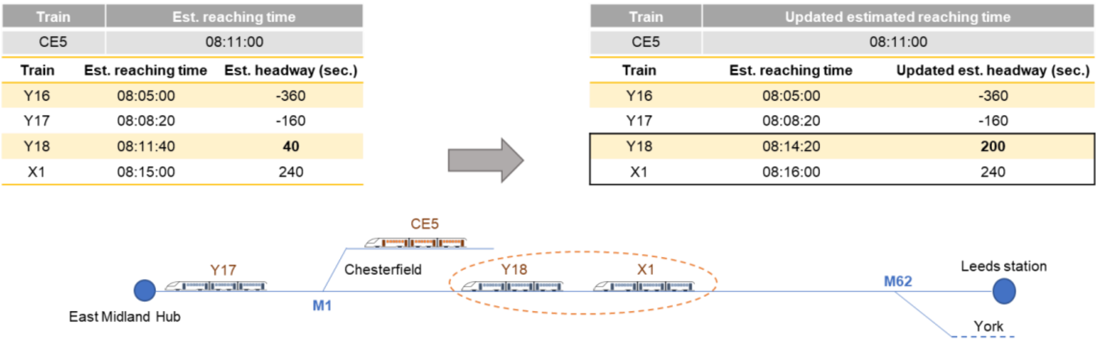
Basically, the train Y12 should be merged as a train convoy with its front train to extend the time gap behind the convoy. However, the train Y12 could not accelerate to be merged into a train convoy due to the velocity limit restricted along the route. Thus, the estimated reaching time of the inserted convoy must be changed. The updated headway time between the inserted convoy and trains on the main route is shown in **Figure 8.8**. The inserted train CE3 and CE4 should pass the M1 junction at 07:55:00 and 07:56:40 respectively. Thus, the extra time gap required in front of the following convoy is at least |-120|+180 = 300 sec. It is seen that the headway time from train CE4 (the last train in the inserted convoy) to train Y13 and Y14 is less than minimum headway time. In this case, both trains will be merged into the same convoy with the reference train Y15 for extending at least 300 sec extra time gap in front of the train Y13. The optimal merging velocity of the train Y13 is

$$\mathrm{v}_{\mathrm{Y12}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{Y15}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{Y12}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 100 \Big/ \left(1 + \left(\frac{30000}{61720}\right)\right) = 67 \mathrm{~m/s}$$

Thus, the optimal merging velocity of the train Y13, Y14 and Y15 is 67 m/s, 83 m/s, 100 m/s respectively.

8.4.1.4 Inserting the train CE5

Assuming that the train CE5 has a higher braking rate than the trains operating on the main route. At least 150 sec headway time away from its front train is required for passing the M1 junction safely. By comparing the estimated reaching time shown in **Figure 8.9 (left)**, the train CE 5 will be inserted into the main route between train Y17 and train Y18. It is found that the headway time between the inserted train CE5 and its leading train (train Y17) is 160 sec. It is higher than the required minimum headway time at 150 sec. In this case, the train CE5 could operate by its ideal velocity and could reach the M1 junction by its original estimated reaching time.



Train	Est. reaching time
CE5	08:11:00

Train	Est. reaching time	Est. headway (sec.)
Y16	08:05:00	-360
Y17	08:08:20	-160
Y18	08:11:40	**40**
X1	08:15:00	240

Train	Updated estimated reaching time
CE5	08:11:00

Train	Est. reaching time	Updated est. headway (sec.)
Y16	08:05:00	-360
Y17	08:08:20	-160
Y18	08:14:20	**200**
X1	08:16:00	240

Figure 8.9 Estimated headway time between CE5 and the involved trains

The headway time from the train CE5 and its following train is only 40 sec. Thus, at least 160 sec extra headway time behind the train CE5 is required. Because the train Y18 is the last train within the defined time period, it has to be merged as the same convoy with the train in the next operating hour. Assuming that the headway time from the train X1 (the first train in the next operating hour) to the train Y18 and the inserted train CE5 is 200 sec and 240 sec respectively. Only the headway time between train CE5 and Y18 is unsafe, in which it is less than the minimum headway time at 200 sec. Thus, the train Y18 should be merged as the following convoy behind the inserted train CE5 with the reference train X1. The optimal merging velocity of the train Y18 is

$$\mathrm{v}_{\mathrm{Y18}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{X1}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{Y18}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 100 \Big/ \left(1 + \left(\frac{16000}{61720}\right)\right) = 79\ \mathrm{m/s}$$

The optimal merging velocities and the updated estimated reaching times at M1 junction of all 18 trains are summarized in **Table 8.3**. According to the updated estimated reaching time at the M1 junction after building train convoys, the time gap (headway time) between successive trains in the same convoy is decreased. Also, the time in front of and/or behind the train convoy is increased allowing more trains to be inserted.

Table 8.3 The planned timetable and optimal merging velocity of trains from Yorkshire to EMH

Train	Est. reaching time	Merging velocity (m/s)	Train	Est. reaching time	Merging velocity (m/s)
Y1	07:15:00	100	**Y10**	07:45:00	100
Y2	07:18:20	100	**Y11**	07:48:20	100
Y3	07:25:00	76	**Y12**	07:51:40	100
Y4	07:26:40	88	**Y13**	08:00:00	67
Y5	07:28:20	100	**Y14**	08:00:50	83
Y6	07:31:40	100	**Y15**	08:01:40	100
Y7	07:35:00	100	**Y16**	08:05:00	100
Y8	07:42:20	72	**Y17**	08:08:20	100
Y9	07:43:40	86	**Y18**	08:14:20	79

8.4.2 From East Midland Hub to Yorkshire

Assuming that trains will depart from the East Midlands Hub station to Yorkshire in every 200 sec dispatching headway time. Based on their ideal velocity profile shown in **Figure 8.5**, they will reach the M1 junction by estimated reaching time shown in **Table 8.4**. Assuming that there are five trains (CY1, CY2, CY3, CY4, and CY5) from the Chesterfield route will be inserted into the main route continuing up to Yorkshire. The estimated time that they will reach the M1 junction is 07:12:30, 07:28:30, 07:44:00, 07:45:00, and 07:58:00 respectively.

Table 8.4 Original timetable for trains from East Midland Hub to Yorkshire

Train	Dispatching time	Passing M1	Train	Dispatching time	Passing M1
E1	07:03:20	07:12:30	**E10**	07:33:20	07:42:30
E2	07:06:40	07:15:50	**E11**	07:36:40	07:45:50
E3	07:10:00	07:19:10	**E12**	07:40:00	07:49:10
E4	07:13:20	07:22:30	**E13**	07:43:20	07:52:30
E5	07:16:40	07:25:50	**E14**	07:46:40	07:55:50
E6	07:20:00	07:29:10	**E15**	07:50:00	07:59:10
E7	07:23:20	07:32:30	**E16**	07:53:20	08:02:30
E8	07:26:40	07:35:50	**E17**	07:56:40	08:05:50
E9	07:30:00	07:39:10	**E18**	08:00:00	08:09:10

Because the successive trains could be built as a train convoy since they depart from the station, the dispatching headway time between trains that will be merged into the same convoy could be decreased. In this part, the dispatching time of some trains on the main route will be adjusted in order to increase the time gap for inserting trains from Chesterfield route.

8.4.2.1 Inserting the train CY1

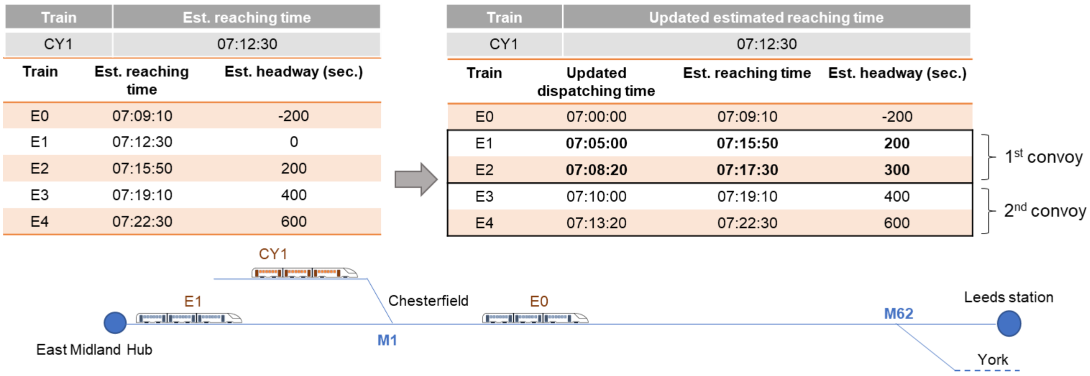
Referring to the original estimated reaching time in **Table 8.4**, the train CY1 will be inserted into the main route in front of the train E1. There is no time gap separated from the train E1, in which they will reach the M1 junction at the same time. In this case, at least 200 sec extra time gap in front of the train E1 is required. The approach and flowchart in **Section 3.4** is used to create a new timetable and **Equation (3-57)** is used to calculate the optimal merging velocity.

The train E1, train E2, and train E3 could be merged into the same convoy in order to extend the time gap for inserting the train CY1. In this case, the first train (train E1) in the convoy should decelerate to 39 m/s for merged into the same convoy with the train E2 and train E3. Its merging velocity is too low that might cause a huge delay. In the case that the train E2 and E3 continue on different routes (one to Leeds and another one to York), building them together into the same convoy might increase their travel time because they have to decelerate to low velocity for splitting out from the convoy when approaching the M62 junction.

To prevent a huge delay, the idea is to build more convoys instead for extending 200 sec extra time gap in front of the train E1. In this case, two convoys including four trains (two trains in each convoy) could be built because another inserted train that will be inserted behind the train E4. Assuming that 100 sec extra time gap is required in front of each convoy. The optimal merging velocity of the first train in each convoy (Train E1 and Train E3) is

$$\mathrm{v}_{\mathrm{E1}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{E2}}^{\mathrm{mer}} \Big/ \left(1+\left(\frac{\Delta \mathrm{x}_{\mathrm{E1}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1+\left(\frac{6000}{22700}\right)\right) = 47\ \mathrm{m/s}.$$

The headway time in front of the train E1 should be extended by at least 200 sec. However, building the train E1 and train E2 together as a train convoy will extend the headway time in front of the train E1 from 200 sec to only 300 sec. Because the train E3 and train E4 are built into the same convoy as well, the headway time in front of the train E3 is increased from 200 sec to 300 sec. However, the headway time required in front of the train E3 is only 200 sec. Thus, the dispatching headway time between train E2 and E3 could be reduced from 200 sec to 100 sec. Consequently, the headway time between them will be increased from 100 sec to 200 sec when they pass the junction.



Train	Est. reaching time
CY1	07:12:30

Train	Est. reaching time	Est. headway (sec.)
E0	07:09:10	-200
E1	07:12:30	0
E2	07:15:50	200
E3	07:19:10	400
E4	07:22:30	600

Train	Updated estimated reaching time
CY1	07:12:30

Train	Updated dispatching time	Est. reaching time	Est. headway (sec.)	
E0	07:00:00	07:09:10	-200	
E1	**07:05:00**	**07:15:50**	**200**	1st convoy
E2	**07:08:20**	**07:17:30**	**300**	
E3	07:10:00	07:19:10	400	2nd convoy
E4	07:13:20	07:22:30	600	

Figure 8.10 Estimated headway time between CY1 and the involved trains

Thus, the dispatching time of the train E1 and E2 could be adjusted as shown in **Figure 8.10**. By adjusting the dispatching time, the headway time between train E0 and E1 could be extended to 400 sec which is high enough to insert the train CY1.

8.4.2.2 Inserting the train CY2

According to the estimated reaching time at the M1 junction shown in **Table 8.4**, the train CY2 will be inserted into the main route between train E5 and E6. Assuming that the braking rate of the train CY2 is lower than the braking rate of the train E5 requiring at least 240 sec headway time between them. Thus, the estimated reaching time of the train CY2 will be changed from 07:28:30 to 07:29:50 for maintaining safe headway time from the train E5. To increase the headway time for inserting the train CY2, the train E6, train E7, and train E8 should merged together into the same train convoy. As the train E7 and train E8 will continue on different routes (one to Leeds and one to York), they should not be built into the same convoy because they need to decelerate using low velocity for splitting out from a convoy.

Similar to the approach used for inserting the train CY1, two train convoys (two trains in each convoy) will be created instead of one train convoy (three trains in a convoy). The dispatching headway time between train E7 and train B8 could be reduced. Assuming that the extra headway time required in front of the first and the second convoy is 140 sec and 100 sec respectively. Thus, the optimal merging velocity of the first train in the first convoy (train E6) is

$$\mathrm{v}_{\mathrm{E6}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{E7}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{E6}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{8400}{22700}\right)\right) = 43\ \mathrm{m/s}$$

The train E6 and train E7 will be merged into the same convoy using 43 m/s and 60 m/s merging velocity respectively. As a result, the headway time in front of the convoy will be increased from 200 sec to 340 sec. However, at least 440 sec headway time in front of the convoy is required. Thus, an extra 100 headway time in front of the train E8 is required. The optimal merging velocity of the first train in the second convoy (train E8) is

$$\mathrm{v}_{\mathrm{E8}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{E9}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{E8}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{6000}{22700}\right)\right) = 47\ \mathrm{m/s}$$

By building the train E8 and train E9 as a train convoy using 47 m/s and 60 m/s merging velocity, the headway time in front of the train E8 will be increased by 100 sec. The headway time in front of the train E8 is increased from 200 sec to 300 sec when it passes the M1 junction but the safe headway time between train E7 and train E8 at the junction is only 200 sec. Thus, the dispatching headway time between train E7 and E8 could be reduced by 100 sec. As a result, the headway time between them when passing through M1 junction is 200 sec that is high enough for passing the junction safely. The dispatching time of the train E6 and E7 is changed to 07:21:40 and 07:25:00 respectively (**Figure 8.11**). The dispatching headway time between train E5 and E6 is 300 sec. It will be increased from 300 sec to 440 sec by building train E6 and train E7, train E8 and E9 as train convoys.

Train	Est. reaching time
CY2	07:28:30

Train	Est. reaching time	Est. headway (sec.)
E5	07:25:50	-160
E6	07:29:10	40
E7	07:32:30	240
E8	07:35:50	440
E9	07:39:10	640

Train	Updated estimated reaching time
CY2	**07:29:50**

Train	Updated dispatching time	Est. reaching time	Est. headway (sec.)
E5	07:16:40	07:25:50	-240
E6	**07:21:40**	**07:33:10**	**200**
E7	**07:25:00**	**07:34:10**	**260**
E8	07:26:40	07:35:50	360
E9	07:30:00	07:39:10	500

1st convoy

2nd convoy

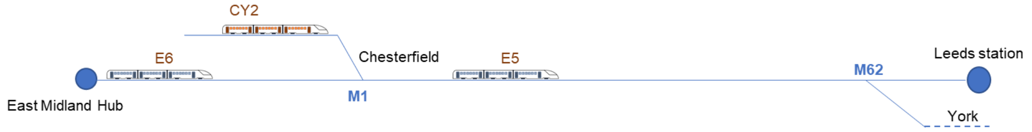
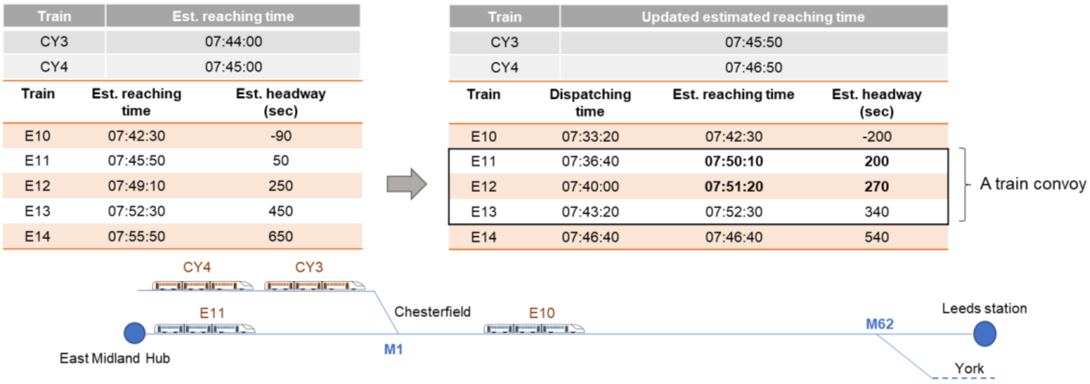


Figure 8.11 Estimated headway time between CY2 and the involved trains

8.4.2.3 Inserting the train convoy: train CY3 and train CY4

Assuming that the train CY3 and CY4 has been built as the same convoy keeping 60 sec headway time between them. They will reach the M1 at 07:44:00 and 07:45:00 respectively. Based on the original timetable, the estimated headway time between the first train of inserted convoy and its leading train (train E10 on the main route) is 90 sec. It is lower than the minimum headway time at 200 sec for passing through M1 junction safely.

To maintain safe headway time away from the trains on the main route, the inserted convoy should slow down and should reach the M1 by the updated time shown in **Figure 8.12**. After updating the estimated reaching time of the inserted trains, it is found that the headway time between the last train in the inserted convoy (train CY4) and the first train in the following group (train E11) is 60 sec. However, the train E11 will reach the junction earlier than the train CY4. Thus, |-60|+200 = 260 sec extra headway time in front of the train E11 is required. In this case, train E11, train E12, and train E13 will be built into the same convoy. In this case, only 1 convoy will be built, and the dispatching time of the involved train is not changed. This is because there is another train will be inserted between train E14 and train E15. The train E14 should not be built into a convoy for preventing delay, in which it has to decelerate for splitting out from a convoy when approaching M62 junction.



Train	Est. reaching time
CY3	07:44:00
CY4	07:45:00

Train	Est. reaching time	Est. headway (sec)
E10	07:42:30	-90
E11	07:45:50	50
E12	07:49:10	250
E13	07:52:30	450
E14	07:55:50	650

Train	Updated estimated reaching time
CY3	07:45:50
CY4	07:46:50

Train	Dispatching time	Est. reaching time	Est. headway (sec)
E10	07:33:20	07:42:30	-200
E11	07:36:40	**07:50:10**	**200**
E12	07:40:00	**07:51:20**	**270**
E13	07:43:20	07:52:30	340
E14	07:46:40	07:46:40	540

A train convoy

Figure 8.12 Estimated headway time between a train convoy (CY3 and CY4) and the involved trains

The optimal merging velocity for the first train in this convoy (train E11) is

$$v_{E11}^{mer} = v_{E13}^{mer} \Big/ \left(1 + \left(\frac{\Delta x_{E11}^{ext}}{\Delta x^{mer}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{15600}{22700}\right)\right) = 35 \text{ m/s}$$

and the optimal merging velocity of the middle train is

$$v_{E12}^{mer} = 35 + 13 = 48 \text{ m/s}$$

After building these three trains as the train convoy by using the optimal merging velocities suggested above, the estimated reaching times and headway time between the inserted convoy and the involved trains are updated as shown in right table in **Figure 8.12**.

8.4.2.4 Inserting the train CY5

Assuming that the last inserted train CY5 has high braking capability requiring 150 sec minimum headway time away from its front train. It will reach the M1 junction at 07:58:00 and will be inserted into the main route in front of the train E15. Based on the original timetable shown in **Table 8.4**, the headway time between train E14 and the inserted train CY5 is 130 sec. It is lower than the minimum headway time at 150 sec. In this case, a convoy in front of the inserted train CY5 cannot be built due to velocity limit. Thus, the inserted train CY5 should reach M1 at 07:58:20 for keeping 150 sec away from its leading train E14.

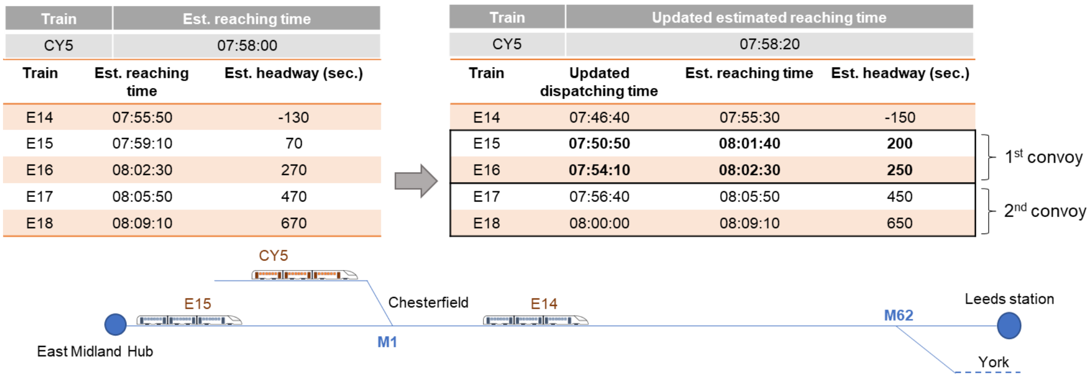
The updated estimated reaching time of the train CY5 and its headway time away from the involved trains is shown in **Figure 8.13**. It is seen that the estimated headway time from the train CY5 to the first train in the following convoy (train E15) is only 50 sec. Thus, at least 150 sec headway time in front of the train E15 is required. In this case, the train E15 and train E16 should be merged into the same convoy by 42 m/s and 60 m/s merging velocity respectively. To prevent a hug delay on the train E15, another solution is to build more convoy and reduce the dispatching headway time between the last train in front convoy and the first train in the following convoy. Instead of building only one train convoy (train E15 and E16), we could build 2 convoys including train E15 and train E16 in the first convoy, and train E17 and train E18 in the second convoy. Assuming that the expected extended headway time after building the first and the second convoy is 100 sec and 50 sec respectively. The optimal merging velocity of the train E15 is

$$\mathrm{v}_{\mathrm{E15}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{E16}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{E15}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{9000}{22700}\right)\right) = 47\ \mathrm{m/s}$$

It is higher than the merging velocity calculated from the first solution. The optimal merging velocity for the train E17 is

$$\mathrm{v}_{\mathrm{E17}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{E18}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{E17}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 60 \Big/ \left(1 + \left(\frac{3000}{22700}\right)\right) = 52\ \mathrm{m/s}$$

Building two convoys will increase the time gap between the convoys from 200 sec to 250 sec. However, only 200 sec headway time between them is needed. Thus, the dispatching headway time between train E16 and E17 could be reduced from 200 sec to 150 sec. The dispatching time of the involved trains are updated as shown in **Figure 8.13**.



Train	Est. reaching time	
CY5	07:58:00	
Train	**Est. reaching time**	**Est. headway (sec.)**
E14	07:55:50	-130
E15	07:59:10	70
E16	08:02:30	270
E17	08:05:50	470
E18	08:09:10	670

Train	Updated estimated reaching time			
CY5	07:58:20			
Train	**Updated dispatching time**	**Est. reaching time**	**Est. headway (sec.)**	
E14	07:46:40	07:55:30	-150	
E15	**07:50:50**	**08:01:40**	**200**	1st convoy
E16	**07:54:10**	**08:02:30**	**250**	
E17	07:56:40	08:05:50	450	2nd convoy
E18	08:00:00	08:09:10	650	

Figure 8.13 Estimated headway time between CY5 and the involved trains

The planned dispatching time and optimal merging velocity of 18 trains on the main route are shown in the below.

Table 8.5 Planned timetable and optimal merging velocity for trains from EMH station to Yorkshire (Leeds and York station)

Train	Dispatching time	Opt. merging velocity (m/s)	Train	Dispatching time	Opt. merging velocity (m/s)
E1	**07:05:00**	47	E10	07:33:20	60
E2	**07:08:20**	60	E11	07:36:40	36
E3	07:10:00	47	E12	07:40:00	48
E4	07:13:20	60	E13	07:43:20	60
E5	07:16:40	60	E14	07:46:40	60
E6	**07:21:40**	43	**E15**	**07:50:50**	47
E7	**07:25:00**	60	**E16**	**07:54:10**	60
E8	07:26:40	47	E17	07:56:40	52
E9	07:30:00	60	E18	08:00:00	60

*** Bold:** dispatching time changed

8.5 Operating based on a new timetable

The VCS application (**Section 3.5.3**) is used to merge the involved trains into the train convoy. It is noted that all involved trains must operate on-time (with no delay). After accepting the convoy proposal, the trains will operate based on the proposed approach in **Section 2.3**. They will split out from the train convoy when approaching the M62 junction. The approach in **Section 3.2.2.2** is applied for identifying the optimal splitting point and the splitting velocity. When trains have been merged into the train convoy, they may decelerate causing delay. Thus, the VCS application 1 (**Section 3.5.1**) will be applied to build the delayed and the impacted trains together as a train convoy for reducing secondary delay.

In this section, assuming that the all trains within defined time period have operated based on planned timetable shown in **Table 8.3** (Yorkshire to EMH) and **Table 8.5** (EMH to Yorkshire). The headway times between successive trains when passing through the junction are measured in order to determine whether the trains from Chesterfield could be inserted into the main route safely. The movement of trains in both legs is simulated as shown in the sections below.

8.5.1 From Yorkshire to East Midlands Hub

Figure 8.14 shows the distance-time profile of trains operating based on the planned timetable stated in **Section 8.4.1.** The first train in the defined time period (train Y1) reaches the M1 junction at 07:15:00 while the last train (train Y18) passes the same point at 08:14:30. Five extra trains from Chesterfield could be inserted into the main route. Thus, the route capacity in terms of the number of trains is increased from 18 trains to 23 trains per hour.

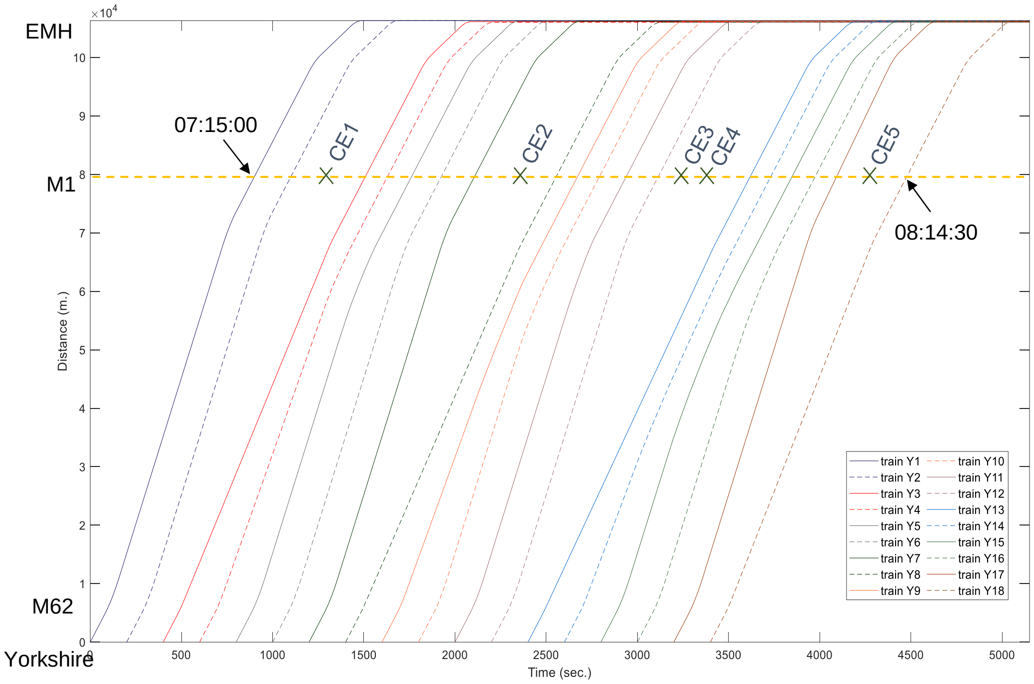


Figure 8.14 Distance-time profile of trains based on planned timetable: from Yorkshire to East Midlands Hub

It could be concluded that the VCS could be used to increase route capacity by building trains as a train convoy for increasing the headway time allowing an extra train to be inserted. However, some trains might delay caused by a train convoy building. As a result, more trains might be built into a train convoy than involved trains stated in the planned timetable for reducing secondary delay. The building of each convoy in operating state is shown below.

8.5.1.1 Inserting the train CE1

The simulated distance-time and velocity-distance profile of the involved trains for inserting the train CE1 are shown in **Figure 8.15**. It is obviously seen that the headway time between train Y2 and Y3 when passing the M1 junction is increased from 200 sec to 410 sec. It is high enough to insert the train CE1 into the main route safely (at least 400 sec headway time is required to insert the train CE1).

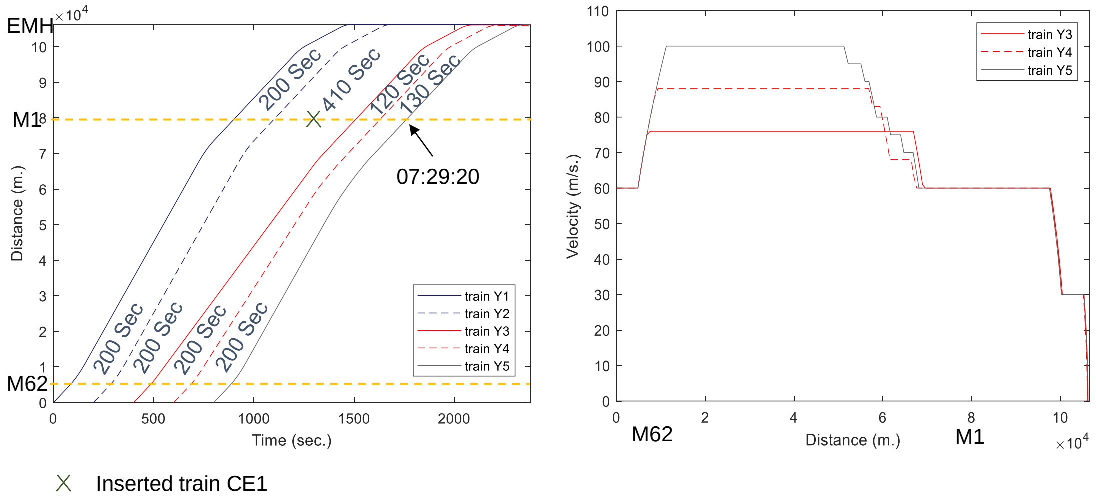
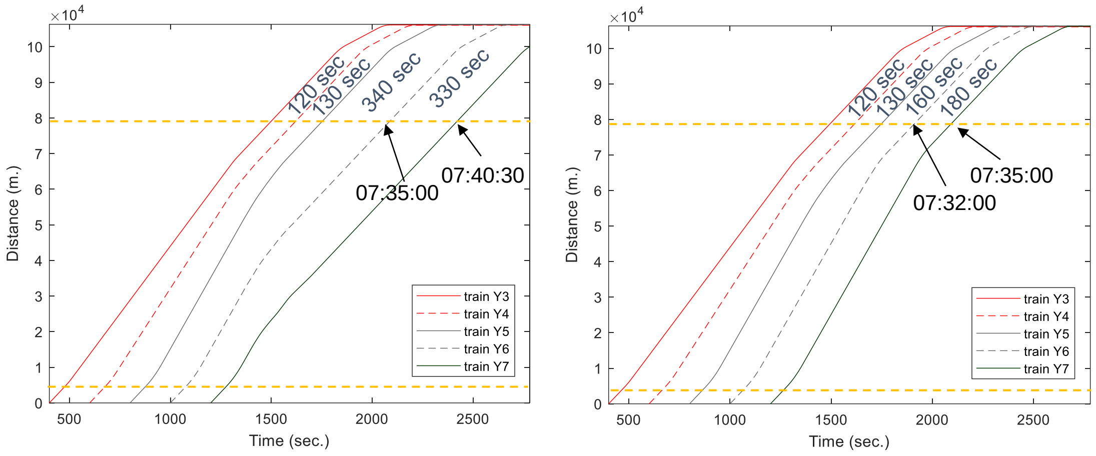


Figure 8.15 Headway time and velocity-distance profile of involved trains built as a convoy for inserting train CE1

However, the last train in the convoy (train Y5) will arrive at M1 junction at 07:29:20 late than the estimated reaching time for 60 sec. It impacts its following train movement (train Y6) because the headway time between them is reduced to 160 sec which is lower than the 200 sec, minimum headway required for passing through the junction. The train Y6 will decelerate causing delay due to the deceleration for maintaining safe headway from the train Y5. To reduce delay, the VCS application 1 is applied to merge the delayed train (train Y5) and the impacted train (train Y6) into the same convoy to reduce delay.

The distance-time profile of trains without the VCS Application for reducing delay is shown in **Figure 8.16 (a)**. It is seen that the train Y6 and Y7 reach the M1 junction at 07:35:00 and 07:40:30 respectively. This is because they need to maintain the safe distance separated from their front train (at least 20 km with 100 m/s operating velocity). To reduce the secondary delay of the train Y6, the **VCS Application 1** is applied. The distance-time profile after applying the VCS application is shown in **Figure 8.16 (b)**. The train Y6 is merged as the same convoy with the train convoy in front (including train Y3, train Y4, and train Y5). The headway time between train Y6 and its front train Y5 could be reduced to 160 sec causing 20 sec delay compared to the estimated reaching time in the original timetable (See more detail in **Table 8.2**). The delay of train Y6 also impacts on the movement of train Y7. In this case, the train Y7 is also built into the same train convoy with its front trains. Interestingly, the train Y7 could reach the junction on time after applying the VCS application 1 to reduce delay. Thus, it will not impact on the movement of its following trains. If trains have operated without the VCS application 1, the train Y7 will reach the junction at approximately 07:40:30 causing 330 sec delayed. Moreover, it will impact on the movement of the following trains forcing them to decelerate causing delay as well.



(a) (b)

Figure 8.16 Distance-time profile (a) without and (b) with VCS application to reduce delay time when inserting train CE1

According to the planned timetable, only three trains will be built into the same convoy for increasing the headway time allowing the train CE1 to be inserted into the main route. But in the operating state, building train Y3, Y4, and Y5 together impact the movement of the trains proceeding behind forcing them to decelerate causing delay. In operating state, the train Y6 and train Y7 have to be built into the same convoy with the trains for reducing delay.

8.5.1.2 Inserting the train CE2

The simulated distance-time and velocity-distance profile of involved trains for inserting the train CE2 are shown in **Figure 8.17**. It is seen that the headway time between train Y7 and Y8 is obviously increased. It is increased from 200 sec to 450 sec when passing the M1 junction. The train CE2 needs at least 240 sec headway time away from its front train Y7 and at least 200 sec separated from its following train (train Y8). The last train in the convoy (train Y10) reaches the M1 junction at 07:46:30 resulting approximately 90 sec delay compared to the estimated reaching time based on planned timetable. Its delay will affect the trains proceeding behind forcing the following trains to decelerate for maintaining safe headway time.

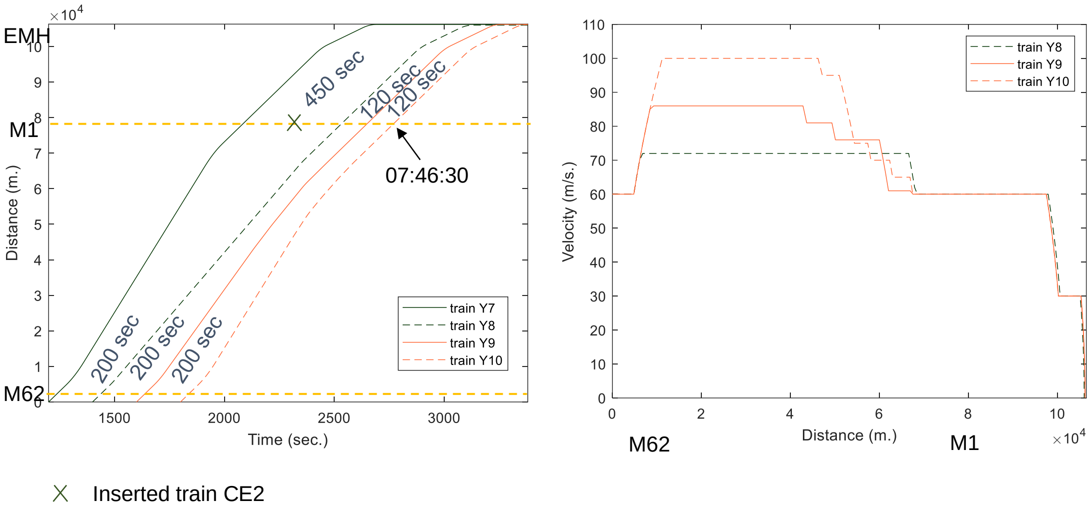
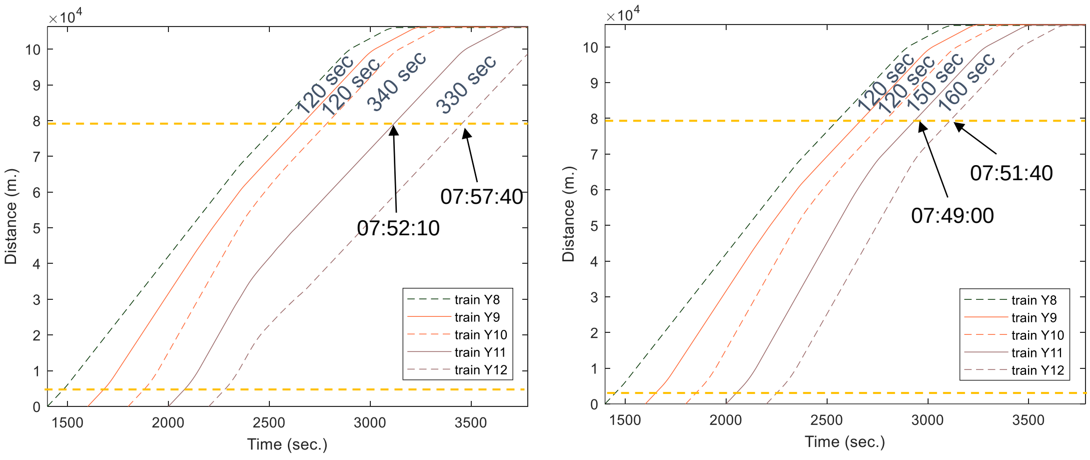


Figure 8.17 Headway time and velocity profile of involved trains built as a convoy for inserting train CE2

The distance-time profile of trains without the VCS Application 1 is shown in **Figure 8.18 (a)**. It is seen that the train Y11 and train Y12 need to slow down for keeping the safe distance separated from their front train. The train Y11 and train Y12 pass the M1 junction at 07:52:10 and 07:57:40 resulting secondary delay for 190 sec and 360 sec respectively. By applying the VCS Application 1 to reduce their secondary delay, their delay could be reduced (**Figure 8.18 (b)**). In addition, the train Y12 could still operate based on its ideal velocity without delay. It has no impact on its following trains.



(a) (b)

Figure 8.18 Distance profile (a) without and (b) with VCS application 1 to reduce delay when inserting train CE2

In planning state, only three trains including train Y8, train Y9, and train Y10 should be built into the same convoy for increasing headway time to insert the train CE2. But in real operation, the train Y11 and Y12 will be merged into the same convoy with three trains in front to reduce delay. The train Y12 could reach the M1 on-time without delay impacting the trains running behind it.

8.5.1.3 Inserting the train CE3 and CE4

Based on the planned timetable, the train Y13, train Y14, and train Y15 will be built together into the same convoy to insert the couple of train CE3 and CE4 into the main route. The simulated distance-time and velocity-distance profile of the involved trains built for inserting a train convoy from Chesterfield is shown in **Figure 8.19**. It is found that the headway time between train Y12 and train Y13 is increased from 200 sec to 520 sec when passing the M1 junction. It is higher than the minimum headway time required for inserting a couple of train CE3 and CE4 into the main route. However, the last train in this convoy (train Y15) will reach the M1 junction at 08:04:10 late than the estimated reaching time. It impacts the movement of its following trains stimulating the following trains to slow down causing delay as shown in **Figure 8.20 (a)**. Applying the VCS Application 1 to build any delayed train and the impacted trains as a train convoy could help trains operating closer together reducing delay.

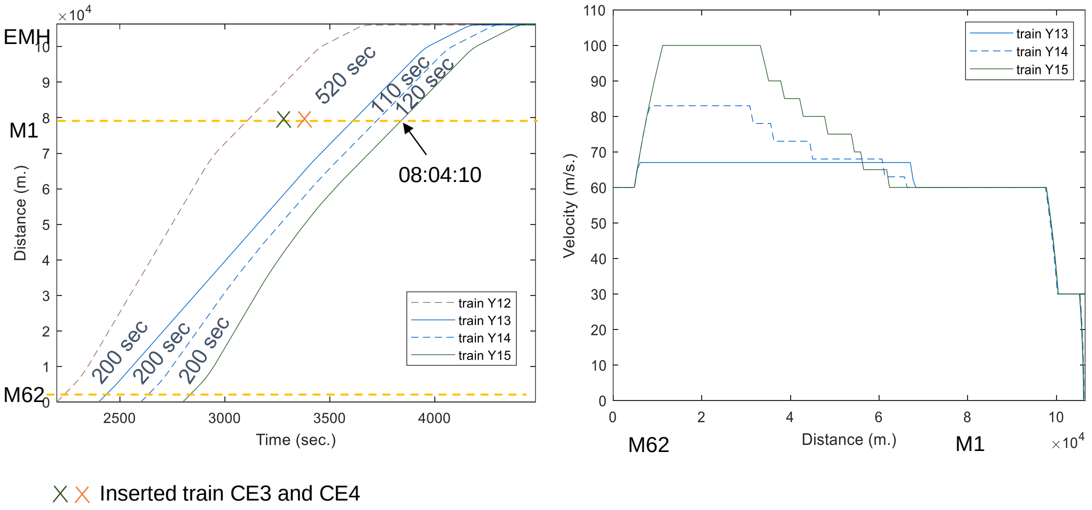
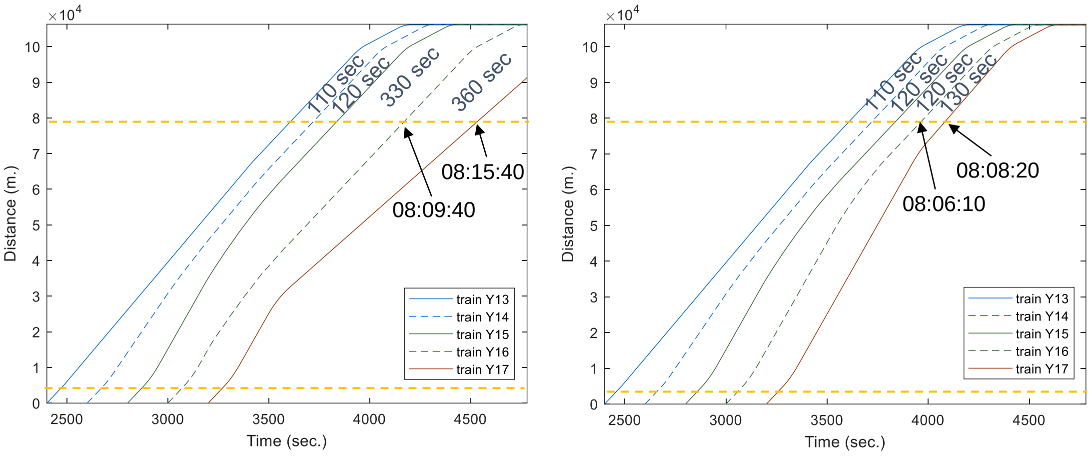


Figure 8.19 Headway time and velocity profile of the involved trains built as a convoy for inserting train CE3 and CE4

As seen in **Figure 8.20 (b)**, the headway times between trains in last two couples are reduced. The train Y17 could operate based on its ideal velocity without delay.



(a) (b)

Figure 8.20 Distance profile (a) without and (b) with VCS application 1 to reduce delay when inserting train CE3 and CE4

Based on planned timetable, three trains including train Y13, train Y14, and train Y15 will be merged into the same convoy in order to extend time gap for inserting a couple of trains from Chesterfield. But in operating state, 2 trains operating behind (train Y16 and Y17) will delay due to the delay of trains in the convoy in front. Thus, they will be merged into the same convoy with three trains in front in order to reduce secondary delay. Thus, five trains are built into the same convoy to extend time gap in front of the convoy for inserting the train CE3 and CE4.

8.5.1.4 Inserting the train CE5

As the inserted train CE5 requires only 150 sec headway time away from its front train. Only two trains including train Y18 and another one train behind (the first train in next operating hour) will be built as the same convoy to increase the time gap in front of train Y18. The simulated distance-time and velocity-distance profile of the involved trains based on planned timetable are shown in **Figure 8.21**. It is seen that the headway time in front of the train Y18 is increased from 200 sec to 370 sec that is high enough to insert the train CE5 into the main route safely.

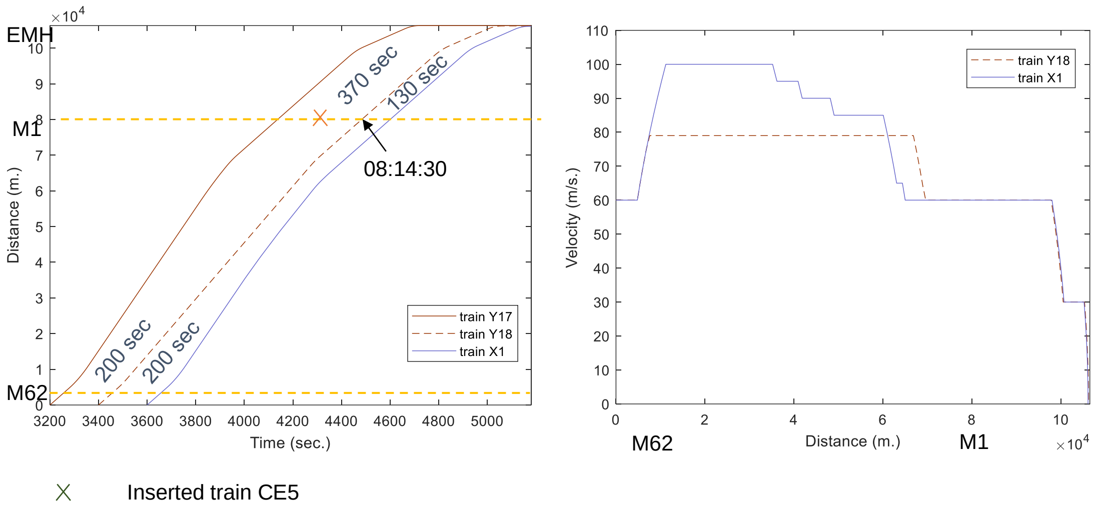


Figure 8.21 Headway time and velocity profile of the involved trains built as a convoy for inserting train CE5

According to the simulated distance-time profile of all trains in one hour defined time period shown in **Figure 8.14**, the first train (train Y1) reaches the M1 junction at 07:15:00 while the last train Y18 reaches the same point at 08:14:30. It could be concluded that if trains have operate based on the MBS, only 18 trains, at maximum, could operate on the same route. However, if they have operated based on the VCS, extra five trains from Chesterfield could be inserted into the main route. As a result, the maximum number of trains could be increased from 18 trains to 23 trains. The simulated reaching times of all trains at M1 junction in operating state are summarized as shown in **Table *8.6***

Table 8.6 Reaching times in planning vs. operating state: Yorkshire to EMH

Train	Est. reaching time	Simulated reaching time	Train	Est. reaching time	Simulated reaching time
Y1	07:15:00	07:15:00	**Y10**	**07:45:00**	**07:46:30**
Y2	07:18:20	07:18:20	**Y11**	**07:48:20**	**07:49:00**
Y3	**07:25:00**	**07:25:10**	**Y12**	07:51:40	07:51:40
Y4	**07:26:40**	**07:27:10**	**Y13**	**08:00:00**	**08:00:20**
Y5	**07:28:20**	**07:29:20**	**Y14**	**08:00:50**	**08:02:10**
Y6	**07:31:40**	**07:32:00**	**Y15**	**08:01:40**	**08:04:10**
Y7	07:35:00	07:35:00	**Y16**	**08:05:00**	**08:06:10**
Y8	07:42:20	07:42:30	**Y17**	**08:08:20**	**08:08:20**
Y9	**07:43:40**	**07:44:30**	**Y18**	**08:14:10**	**08:14:30**

*Bold: the involved trains

8.5.2 From East Midlands Hub station to Yorkshire

The simulated distance-time profile of all 18 trains from EMH station to Yorkshire based on planned timetable is shown in **Figure 8.22**. It is seen that the first train E1 in defined time period passes the M1 at 07:15:50 while the last train E18 reaches the same point at 08:09:00.

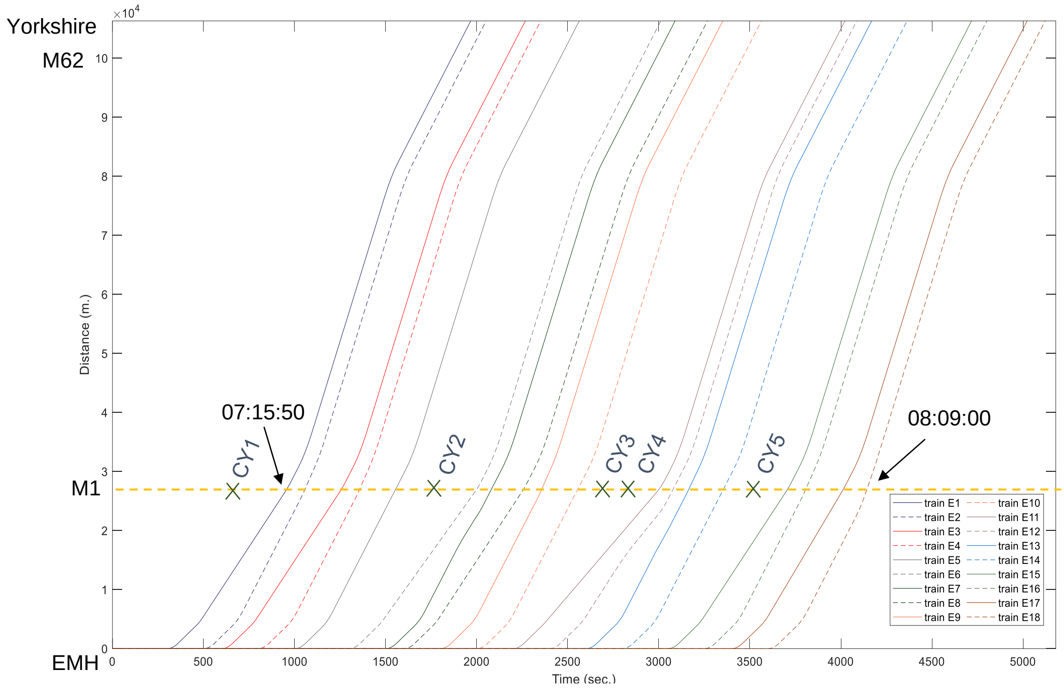
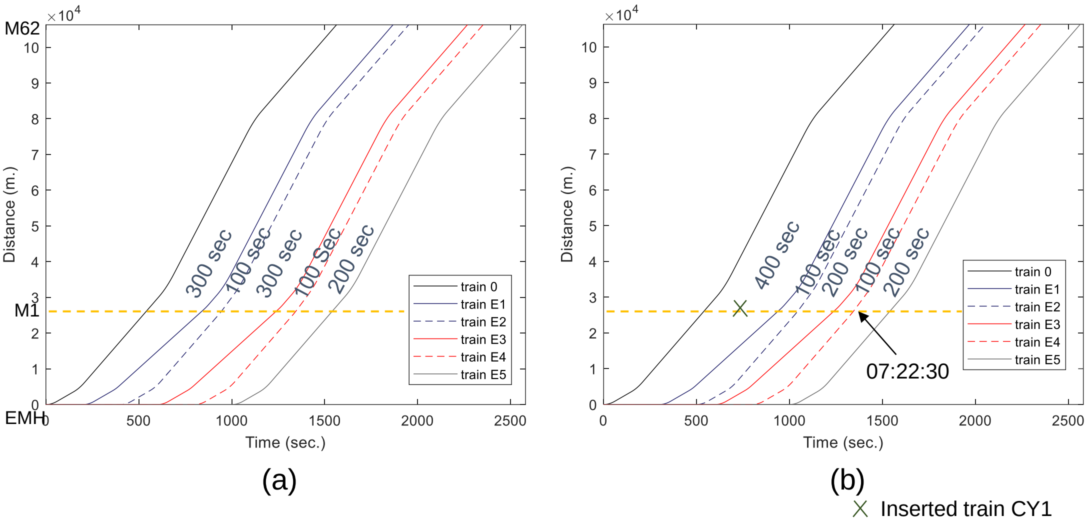


Figure 8.22 Simulated distance-time profile of trains based on planned timetable: from East Midlands Hub station to Yorkshire

It means that five extra trains from Chesterfield could be inserted into the main route increasing route capacity from 18 train to 23 trains.

8.5.2.1 Inserting the train CY1

According to the planned timetable shown in **Section 8.4.2 (1)**, four trains on the main route including train E1 and train E2, and train E3 and train E4 will be merged into convoys to extend the time gap for inserting the train CY1. **Figure 8.23 (a)** shows the simulated distance-time profile of two train convoys before adjusting the dispatching time. It is seen that the headway time in front of each convoy is increased from 200 sec to 300 sec when passing the M1 junction. But at least 400 sec in front of the first convoy is required to insert the train CY1. As the first train in the second convoy (train E3) has operated by a lower velocity than its front train (train E2, last train in the first convoy), the dispatching headway time between them could be reduced. It is reduced from 200 sec to 100 sec. As a result, the headway time between train E2 and train E3 when passing through the M1 junction will be 200 sec that is high enough to pass the junction safely.



(a)

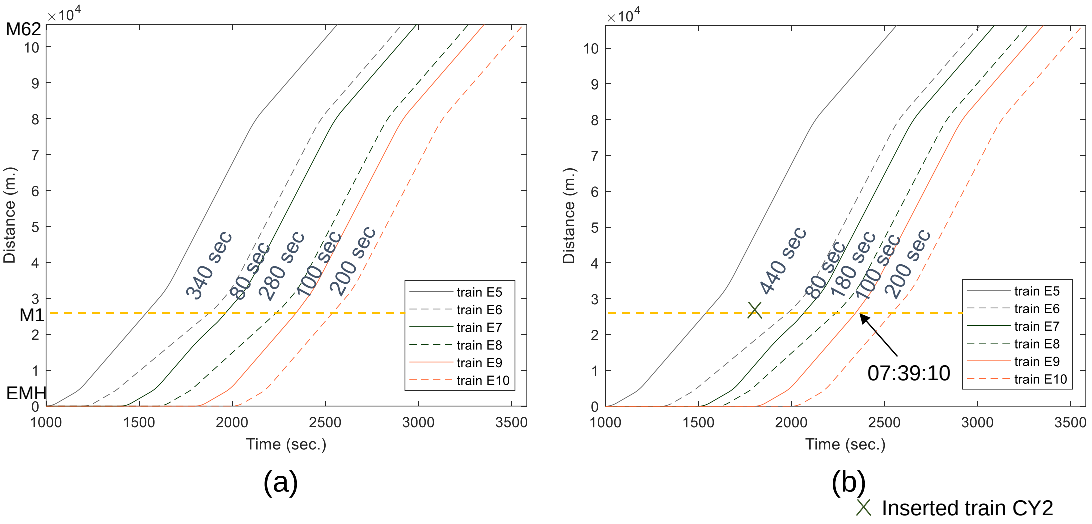
(b)

Figure 8.23 Simulated distance-time profile before (a) and after (b) adjusting the dispatching time for inserting train CY1

The simulated distance-time profile after adjusting the dispatching time is shown in **Figure 8.23 (b)**. It is seen that the headway time in front of the train E1 is increased from 300 sec to 400 sec which is equal to the minimum headway time required for inserting the train CY1. Interestingly, the last train in the second convoy (train E4) could reach the M1 by its expected reaching time without delay. Thus, there is no delay impacting the trains running behind the convoy.

8.5.2.2 Inserting the train CY2

Based on the planned timetable shown in **Section 8.4.2 (2)**, there are two convoys including train E6 and train E7 in the first convoy, and train E8 and train E9 in the second convoy. **Figure 8.24 (a)** shows the distance-time profile of two train convoys before adjusting the dispatching time. It is seen that the headway time between train E5 and train E6 is increased from 200 sec to 340 sec while the headway time between train E7 and train E8 is increased from 200 sec to 280 sec. However, it is found that the headway time between E7 and E8 could not be increased to 300 sec as stated in the planned timetable. This is because the train E7 could not operate by the ideal velocity causing delay reducing the time gap away from the train E8. The train E8 has to slow down for keeping safe headway away from the train E7. It will delay forcing the trains behind to decelerate causing delay as well. To reduce delay, the VCS application 1 is applied to build two convoys together into the same convoy (**Figure 8.24 (b)**). By merging two convoys together, the last train in convoy (train E9) could operate by its ideal velocity and still reach the M1 junction by estimated reaching time with no delay impacting the trains proceeding behind.



(a) (b)

Figure 8.24 Simulated distance-time profile before (a) and after (b) adjusting the dispatching time for inserting train CY2

To sum up, in the planning state, there are 2 convoys built for increasing headway time in front of the train E6 allowing train CY2 to be inserted. However, in real operation, 2 convoys will be built into the same convoy to prevent delay affecting the movement of trains behind.

8.5.2.3 Inserting the train CY3 and CY4

The distance-time and velocity-distance profiles of the involved trains built for inserting the train CY3 and CY4 are shown in **Figure 8.25**. It is seen that the headway time between train E10 and train E11 is increased from 200 sec to 440 sec when passing through the M1 junction. It is high enough to insert the train convoy from Chesterfield safely. However, building this convoy results delay impacting on the movement of the train E14. The VCS Application 1 is applied to merge the train E14 with the convoy in front to prevent delay.

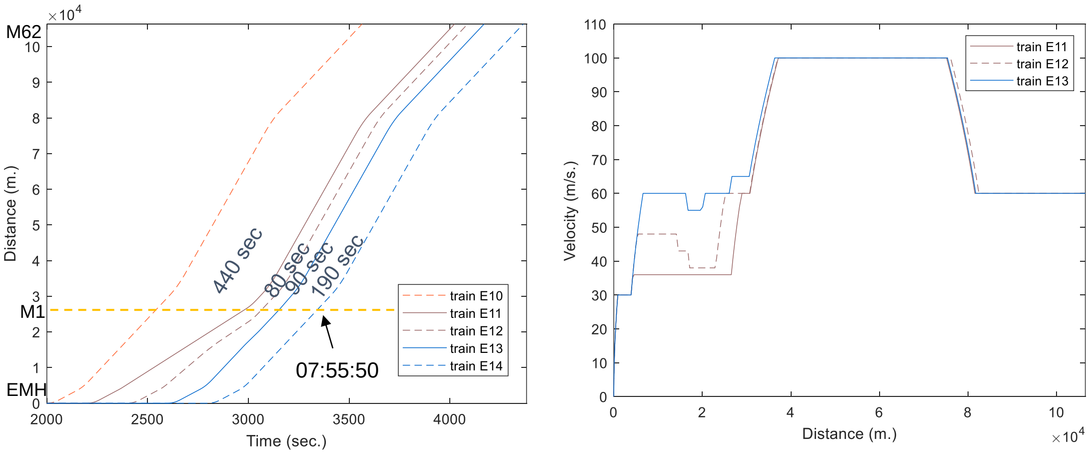
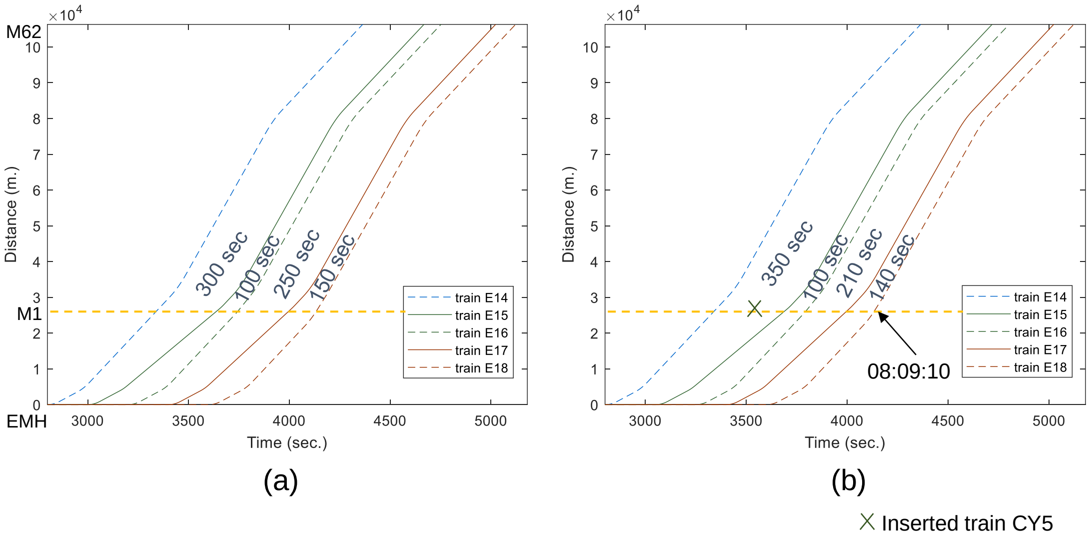


Figure 8.25 Headway time and velocity-distance profile of the involved trains built as convoy for inserting train CY3 and CY4

According to the velocity-distance profile shown in **Figure 8.25**, it is seen that the train E14 could operate based on its ideal velocity and could pass the M1 junction by the estimated reaching time without delay affecting trains running behind. In the planned timetable, three trains including train E11, train E12, and train E13 will be merged into the same convoy to expand time gap for inserting the train CY3 and CY4. However, in operating state, the train E14 will be added into the convoy as well in order to prevent delay impacting the trains operating behind.

8.5.2.4 Inserting the train CY5

For inserting the last inserted train CY5, only 150 sec headway time away from its front train is needed. The simulated distance-time profile of the involved trains before adjusting the dispatching time is shown in **Figure 8.26 (a)**. It is seen that the headway time between train E14 and train E15 is increased to 300 sec when passing the M1 junction. However, to insert the train CY5 between them, the headway time between them when passing the junction should be at least 350 sec.



(a) (b)

Figure 8.26 Simulated distance-time profile before (a) and after (b) adjusting the dispatching time for inserting train CY5

As seen in **Figure 8.26 (a)**, the headway time between the last train in the front convoy (train E16) and the first train in the convoy behind (train E17) when passing the junction is 250 sec. But only 200 sec headway time between them is needed. Therefore, the dispatching time between them could be reduced to 150 sec, in which it will be increased to 200 sec when passing the junction. After adjusting the dispatching time (**Figure 8.26 (b)**), the dispatching headway time between train E14 and train E15 is 250 sec. Thus, the headway time between them when passing the junction will be increased from 250 sec to 350 sec. It is equal to the minimum headway time required for inserting the train CY15 into the main route safely.

The distance-time profile of all trains in one hour time period is shown in **Figure 8.22**. The first train within the defined time period (train E1) will reach the M1 junction at 07:15:50 while the last train (train E18) will reach the same point at 08:09:00. Five trains from Chesterfield route could be inserted into the main route safely. Thus, it could be said that the route capacity in terms of the number of trains could be increased from 18 trains to 23 trains.

The estimated reaching time and the simulated reaching time in operating state of 18 trains when passing the M1 junction are summarized in **Table 8.7**. In operating state, some trains will reach the junction late than the estimated reaching time calculated in the planning state. Thus, more trains will be merged into the same convoy than the involved trains stated in the planned timetable.

Table 8.7 Reaching times in planning vs. operating state: EMH to Yorkshire

Train	Estimated reaching time	Simulated reaching time	Train	Estimated reaching time	Simulated reaching time
E1	**07:12:30**	**07:15:50**	E10	07:42:30	07:42:30
E2	**07:15:50**	**07:17:30**	**E11**	**07:45:50**	**07:49:50**
E3	**07:19:10**	**07:20:50**	**E12**	**07:49:10**	**07:51:10**
E4	07:22:30	07:22:30	**E13**	**07:52:30**	**07:52:40**
E5	07:25:50	07:25:50	E14	07:55:50	07:55:50
E6	**07:29:10**	**07:33:10**	**E15**	**07:59:10**	**08:01:40**
E7	**07:32:30**	**07:34:30**	**E16**	**08:02:30**	**08:03:20**
E8	**07:35:50**	**07:37:30**	**E17**	**08:05:50**	**08:06:50**
E9	07:39:10	07:39:10	E18	08:09:10	08:09:10

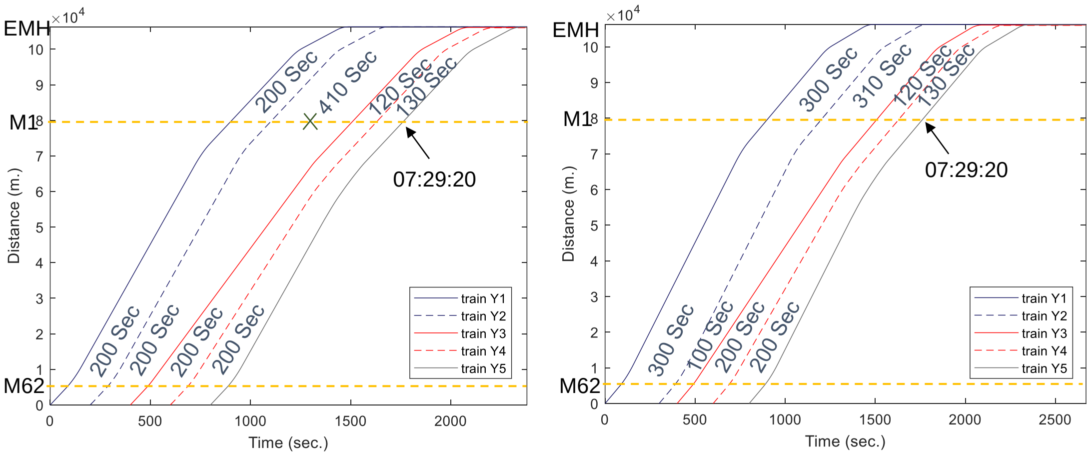
*Bold: the involved trains

8.6 In case of delay before reaching the merging point

In this section, the example in the case that a train could not operate on time before merging as recommended in planned timetable is shown. The **VCS Application 4** (See proposed approach in **Section 3.5.4**) will be applied in order to redetermine the involved trains and recalculate the optimal merging velocity of each train. It is noted that the merging point could be changed. The involved trains and their optimal merging velocity will be re-calculated by the control centre using the current information of the trains when approaching the merging point.

Assuming that the train Y2 (the train operating from Yorkshire to EMH) delays for 100 sec. The train(s) proceeding behind will normally delay as well because the headway time separated from their front train will be less than the minimum headway time under the MBS. In this case, the VCS Application 1 will be applied to reduce secondary delay by merging the delayed train with the impacted trains behind as a train convoy. The delay of the train Y2 only impacts the movement of the train Y3, in that the headway time between them is decreased lowering than the minimum headway required for the MBS.

According to the distance-time profile of trains shown in **Figure 8.27 (b)**, the headway time between train Y2 and train Y3 when passing the M62 junction is reduced from 200 sec to 100 sec due to the delay of the train Y2. In this case, the delayed train Y2 and the impacted train Y3 will be merged as a train convoy in order to reduce delay in the train Y3. It is seen that the train Y3 could operate by its ideal velocity because the headway time from its front train is still higher than minimum headway time required under the VCS. It could operate on time without delay impacting the trains proceeding behind. According to the planned timetable in **Section 8.4.1**, the train Y3 will be merged into the same convoy with the train Y4 and train Y5 in order to increase the time gap allowing the train CE1 to be inserted into the main route. The train Y3 will start splitting from the train Y2 after passing the M62 junction. It has been merged into a new train convoy with the train Y4 and Y5 to reduce delay.



(a)

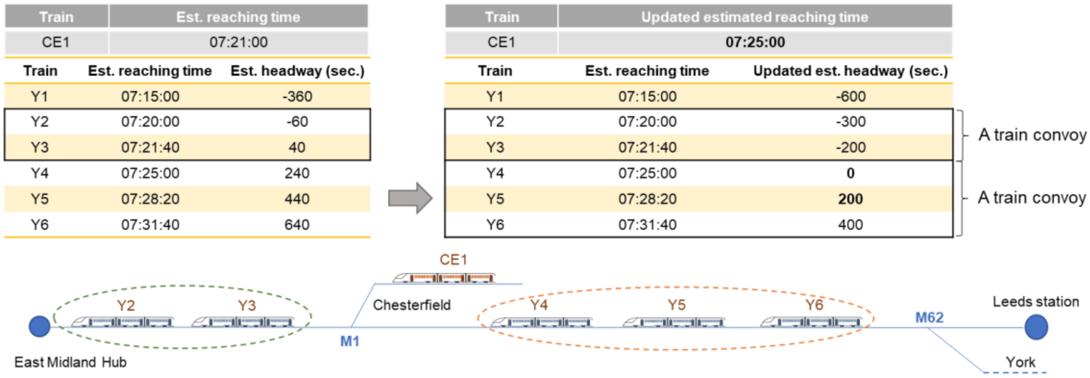
(b)

Figure 8.27 Simulated distance-time profile when the train Y2 (a) operates on time (b) delays

If the train Y3, train Y4, and train Y5 are built into the convoy by using the optimal merging velocity stated in the planned timetable, the headway time between train Y2 and train Y3 when reaching the M1 is only 310 sec. It is less than the expected headway time, 400 sec when the trains have operated on time (**Figure 8.27 (a)**). In this case, the involved trains are redetermined and their optimal merging velocity are re-calculated.

8.6.1 Redetermining the involved trains

The train Y2 is merged into the same convoy (using the VCS application 1) with the train Y3 to reduce delay in the train Y2. They are considered as a single train approaching the merging point. The involved trains for inserting the train CE1 are redetermined by using the current information in operating state. The estimated reaching times of the involved trains are updated as shown in **Figure 8.28**. It is seen that the train CE1 will be inserted into the main route between the train Y3 and train Y4. The inserted train CE1 and the train Y4 will reach the M1 at the same time and the headway time from the train CE1 and train Y5 is equal to the minimum safe headway time.



Train	Est. reaching time
CE1	07:21:00

Train	Est. reaching time	Est. headway (sec.)
Y1	07:15:00	-360
Y2	07:20:00	-60
Y3	07:21:40	40
Y4	07:25:00	240
Y5	07:28:20	440
Y6	07:31:40	640

Train	Updated estimated reaching time
CE1	**07:25:00**

Train	Est. reaching time	Updated est. headway (sec.)
Y1	07:15:00	-600
Y2	07:20:00	-300
Y3	07:21:40	-200
Y4	07:25:00	**0**
Y5	07:28:20	**200**
Y6	07:31:40	400

Figure 8.28 Updated estimated reaching time of new involved trains

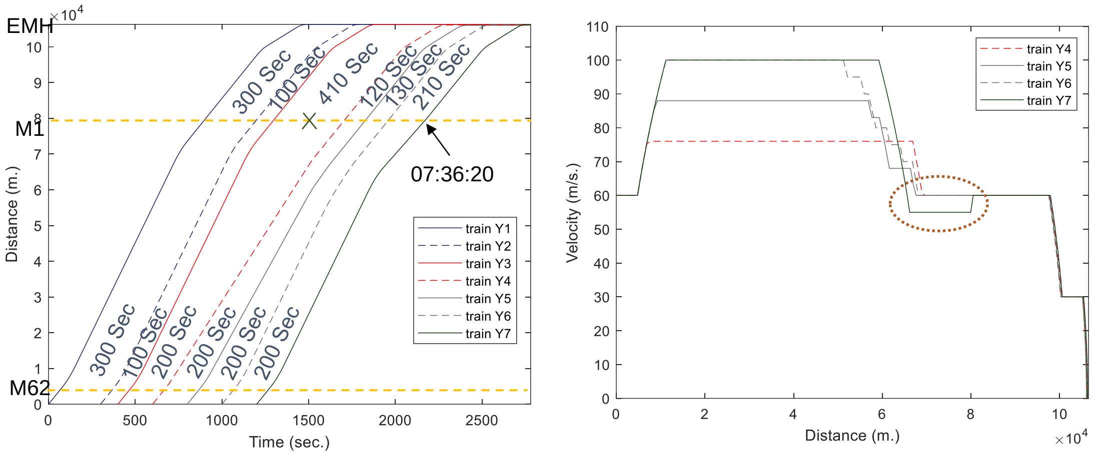
The train Y4 and train Y5 should be merged into the same convoy with the reference train Y6 for lengthening the headway time in front of the convoy. The optimal merging velocity of the train Y4 is

$$\mathrm{v}_{\mathrm{Y4}}^{\mathrm{mer}} = \mathrm{v}_{\mathrm{Y6}}^{\mathrm{mer}} \Big/ \left(1 + \left(\frac{\Delta \mathrm{x}_{\mathrm{Y4}}^{\mathrm{ext}}}{\Delta \mathrm{x}^{\mathrm{mer}}}\right)\right) = 100 \Big/ \left(1 + \left(\frac{20000}{61720}\right)\right) = 76\ \mathrm{m/s}$$

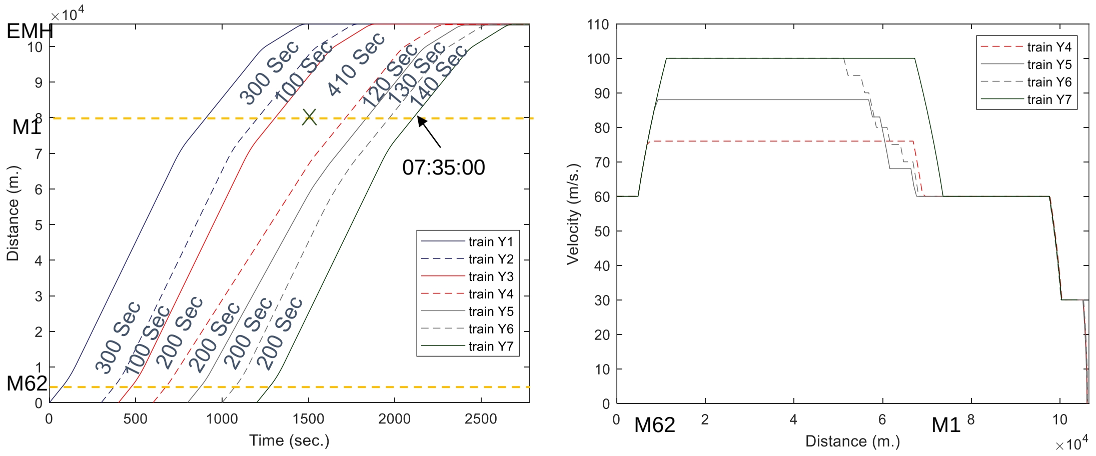
Thus, the train Y4, train Y5, and train Y6 will be merged into the same convoy by using 76 m/s, 88 m/s and 100 m/s merging velocity respectively. It is different from the involved trains in the planned timetable in which the train Y3, train Y4, and train Y5 will be built into the same convoy.

8.6.2 Operating based on updated involved trains

The velocity profile of the new involved trains in operating state is shown in **Figure 8.29**. It is seen that the headway time between train Y3 and train Y4 is increased from 200 sec to 410 sec. It is high enough to insert the train CE1 into the main route safely. However, building the convoy affects the movement of trains behind forcing them to decelerate causing delay. As seen in **Figure 8.29 (a)**, the train Y7 decelerates when the headway time from the train Y6 is less than minimum headway time under the MBS. It will reach the M1 at 07:36:20 causing delay for 80 sec.



(a) without VCS Application 1



× Inserted train CE1

(b) with VCS Application 1

Figure 8.29 Distance-time and velocity-distance profiles of new involved trains for inserting the train CE1

In this case, we could use the VCS application 2 to reduce delay in the train Y7 by merging the train Y7 into the train convoy in front. According to the velocity profile of trains using the VCS to reduce delay shown in **Figure 8.29 (b)**, it is found that the train Y7 could operate by its ideal velocity. It could reach the M1 on-time without delay impacting the movement of its following trains.

8.7 Summary

In the case of full capacity, in which an extra train could not be inserted into the mainline, the VCS approach can be used to increase capacity by recreating a new timetable. Some trains will be merged as a train convoy to insert an extra train. In the case that trains proceed on-time, the involved trains can use the suggested merging velocity and start merging into a convoy when reaching the suggested merging point. According to the simulation results, it is seen that the headway time between convoys measured when passing a converging junction (where an extra train is inserted into the mainline) is increased and is high enough for inserting an extra train. However, in operating state, more trains might be merged into the same convoy (more than the number of involved trains suggested in a new timetable). This is because a delay might occur when building a train convoy. The VCS could also be used to reduce or prevent delay by merging any delayed trains and impacted trains running behind together as a train convoy.

Chapter 9
Conclusion, limitations, and future research

9.1 Conclusion

The research undertaken in this thesis highlights the potential benefits of the next generation of train signalling system - the virtual coupling system – but also identifies that the system has a number of important weaknesses, notably around areas such as inadequate expansion of capacity less capacity, potential unsafe situations, and unstable train movements in terms of highly varying train speeds. They key contributions of this thesis therefore stem from how it develops new approaches based on the VCS for controlling trains operating as a train convoy that address these weaknesses, approaches to creating new timetables to increase route capacity in the case that the number of trains is over route capacity, and in creating train convoys to reduce train delay.

Notably, an approach for controlling train operation based on the distance and velocity different control laws is introduced. In addition, the minimum safe distance equation is modified by adding an additional term in order to ensure that trains can operate safely. Based on simulation results, it can be concluded that the proposed approach can be used to control trains operating under the VCS effectively. Route capacity is increased compared to the capacity under the MBS, trains can operate safely in that the separation distance between trains is longer than minimum safe distance, and a train can maintain a stable speed profile while maintaining adequate and stable headway. It is noted that it is the theoretical maximum number of trains occurs in the case that every pair of two trains are built into the same convoy using the same assumed operational parameters. However, the capacity can vary depending on many parameters such as the number of trains in a convoy, braking capability, etc.

Building a train convoy by using different values may result in different capacity. Hence this thesis also aims to provide a guideline for building train convoys. The capacity consumptions at different values are compared to determine whether these impact on route capacity. As we know the parameters that impact route capacity, we can use the information as a guideline to build train convoys more effectively, in which the distance between trains could be reduced and therefore increasing route capacity.

To increase route capacity, it is important to ensure that the number of trains which can operate along the same route is higher than the maximum capacity under the main signalling control. The contribution here is to use the concept of the VCS to manage a train timetable. Some trains will be merged as a train convoy to increase the headway time (time gap). It can be confirmed that the route capacity can be increased, in that the time gap in front of/behind a train convoy is expanded, allowing an extra train to be inserted onto the route. By following the proposed approach, we can determine whether the VCS should be used, identify which trains and how many trains should be merged into the same convoy, and we can calculate the optimal velocity that a train should proceed for merged into a train convoy.

Another benefit that could be obtained from the VCS is the decrease in delay. It has been shown that building trains together as a train convoy can reduce delay, in which an impacted train will not be forced to decelerate even though the separation distance between them is shorter than the absolute braking distance.

Although these contributions will allow development of VCS to move forward, there are still other limitations that will limit the usage of the proposed approach. The proposed approach cannot be used well in urban rail networks where there are both low and high-speed trains operating along the same route, for example. A range of such limitations is discussed below.

9.2 Limitations

According to the simulation results presented in this thesis, it can be concluded that the proposed equations, flowcharts, and approaches based on VCS could be used effectively to increase the route capacity and reduce secondary delay. However, they have some limitations that can limit the benefit from the VCS.

9.2.1 Train types

The proposed approach could only be used for building trains that have the same characteristics into the same convoy. The proposed approach may not be used well in urban rail transit where there may be different train types proceeding on the same route. Merging two different speeds of train into the same convoy will limit the performance of the trains. In the other words, high and low-speed trains could not be built together into the same convoy. The high-speed train could not accelerate to the top velocity when proceeding behind a lower train. The low-speed train could not speed up to catch up with the high-speed train. Thus, the distance between trains is lengthened reducing route capacity.

9.2.2 Merging trains from different routes as a train convoy

When trains pass through a converging junction, the separation distance between trains from different routes should be at least the minimum safe distance required for passing through a junction. Some trains may have to slow down approaching the junction for maintaining such safe distance from a train ahead. Building convoys of trains after such merging onto a route at a junction would require the leading train to decelerate, and so could be delayed. This reduces the benefit of convoys in such situations.

9.2.3 Splitting distance

The splitting distance calculated from the proposed approach is quite long, as it depends on the splitting velocity difference between successive trains. Using a higher velocity difference for splitting could reduce the length of splitting distance. However, this may delay the train being split from the convoy as it decelerates at a faster rate, and would also result in a less smooth speed profile.

9.2.4 Major delay

In this thesis, we do not consider the use of the VCS application to reduce major delay. This is because the reduction in delay will be limited by the minimum headway time required for the VCS and this may be unlikely to help significantly in reduction of major delay, though this is still to be determined.

9.3 Future research

According to the limitations of the thesis mentioned above, we provide some suggestions for future research to further improve the control of trains under the VCS. In addition, some interesting points that should be considered when controlling trains under the VCS are also suggested.

9.3.1 Using the VCS for managing trains on urban rail transit

The proposed approach could only be used to build trains that have the same characteristics into the same convoy. It is not suitable for controlling trains operating on the urban railway that has both low and high-speed trains operating on the same route. To improve the approach, additional condition(s) will need to be added into the proposed approach for identifying which types of train to couple together into a convoy. Another possibility is to build different train types (low and higher speed trains) together for a while, but split out when a higher speed train needs to speed up.

9.3.2 Building a convoy of trains from different routes

Building on the limitation in section 9.2.2., more consideration is needed into potential strategies for building convoys of trains which have merged from different routes at a converging junction.

9.3.3 Reducing splitting distance

It could be said that the proposed approach is most suitable for controlling trains operating on routes with long station spacing such as high-speed routes. When a train convoy operates along routes with short station spacing, the splitting distance is too short forcing a following train to operate with very low velocity causing delay. In some studies such as the study by Quaglietta et al. (2020), the splitting distance is short but it could be used only in the case that only two trains have been coupled into a train convoy. In future work, the approach for splitting trains could be developed in order to reduce splitting distance.

9.3.4 Using the VCS to reduce major delay

In this thesis, we use the VCS application to reduce minor delay only. In the future study, the VCS application for reducing delay will be developed for reducing major delay.

9.3.5 Operating at a station

In this thesis, we only consider the case that all trains slow down and stop at the same station. But, in real operation, some trains will stop, some will pass through any intermediate station. In the case that a front train slows down to stop at the next station, but a following train will pass through the station, the question is whether they could be built into the same convoy. In the future work, this factor; stopping at stations, will be considered and added into the approach for determining the involved trains in a train convoy.

9.3.6 Determining the energy consumption

Previous studies on VCS have mentioned that VCS could be used to increase route capacity and also reduce energy consumption (Quaglietta, 2018). Energy consumption is lower compared to the energy used under the ETCS Level 2 and Level 3 (Lamas, Carames, & Luis, 2017). In the thesis, only the benefit of the VCS in part of the increasing in route capacity is determined, and the signaling performance to reduce energy consumption is ignored. Based on the proposed approach, it could be presumed that the rate of energy consumption could be reduced because the trains under the proposed approach could maintain more stable travelling speeds. In future studies, energy consumption under the proposed approaches will be considered.

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Appendix A
Evaluation of train signalling system

The railway signaling system refers to all the systems used to control trains proceeding safely preventing collision between them. The development of the railway signalling system in Europe is illustrated in the **Figure A.1**. It starts from the control by train dispatchers who will stand at every block section in order to inform the train driver that whether a train has passed their section. Trains have operated based on the concept that at any one time, each block section could be occupied by only one train. Train dispatchers will allow the train entering their section when the section is not occupied by other trains. However, accident could occur due to human error.

To prevent accident caused from human error, the signal sign called semaphore was introduced and began to use in Europe in 1900. The movement authority is indicated by the position of the signal arm (Palumbo, 2013). As the development of telephone communication system, it allows the train driver communicating directly to the block section's staff. New signalling system named "phone block signalling" was introduced. The train driver will call the staff to ask whether the next block section is clear. Currently, the railway signalling system is still developed based on this concept. But, instead of phone block, the route is equipped with automatic block. This system is generally called "Fixed Block Signalling (FBS). The route is divided into block sections equipped with interlocking. The length of block section must be longer than the absolute blacking distance of the fastest train operating along the route. The movement authority of the train is indicated by the signal lights where green signal informs the driver that the next two block sections are clear allowing the train proceeding subjected to velocity limit, yellow light notifies the driver to prepare to stop because the next two block is already occupied by another train, and the red light warns the drivers to stop (railwaysignalling.eu, 2013). Thus, managing trains operating under the FBS safely, it is necessary to ensure that any one block is occupied by only one train at any one time.

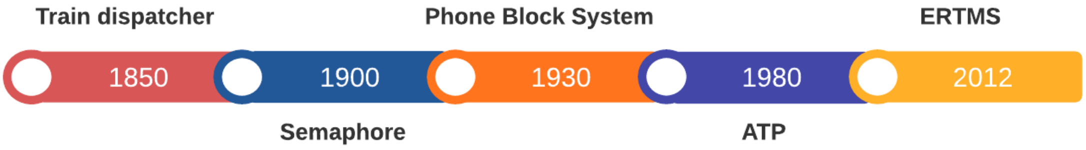

Figure A.1 Evaluation of signaling system (Modified from Palumbo (2013))

To help the train operate more safely, the safety system called "Automatic Train Protection (ATC)" is introduced. The train's velocity profile has been continuously monitored to check whether the train’s velocity exceeding than velocity limit. The ATP will warn the train driver in the case that train passed a red signal, or its current velocity is higher than velocity restriction. In Europe, the railway operation has been developed mainly in order to improve interoperable standard for railway operation in whole area. It is based on the idea that the trains from different origins that might equipped with different systems could operate together. However, in European countries, different ATP systems have currently been used.

Appendix B
Signalling Controls based on ETCS

The train signalling system has mainly been developed regarding capacity, safety, and interoperation system in which the trains from different countries could proceed to other countries without disruption. However, the main problem is different signalling systems equipped in each route that will limit European integration. The European Railway Traffic Management System (ERTMS) is introduced for improving interoperability and performance regarding safety, accessibility, and compatibility (Palumbo, 2013). It is essentially created to develop the high-speed line enhancing cross-border compatibility of railway system in Europe. It is currently the most common railway signalling system installed in many European counties. The trains within the European countries can operate across to another area by using compatible signalling system.

The ERTMS comprises the European Train Control System (ETCS), the Global System for Mobile Communication Trains for Railway (GSM-R), and operating rules managing trains operating together. The ETCS can be considered as the main feature of ERTMS providing two function including Automatic Train Protection (ATP), and cab signalling (Havryliuk, 2017). The ATP is introduced to increase safety by monitoring real time velocity of the train. The system has warned a train driver in the case that a train proceed by a higher velocity than velocity limit. If the diver does not respond to the warning, the emergency brake will be applied (railwaysignalling.eu, 2013). The ETCS is divided as the level depending on the operating control, the cooperation between trains and track, the communication between track side information and on-board computer installed in the trains (UNIFE, 2018). Currently, there are practically four levels of signalling controls based on ETCS.

1. ETCS level 1

The ETCS level 1 is upgraded from the phone block signaling system equipped with the lineside signaling by adding ATP and interlocking system. It is also called “the cab signaling system”. The train will operate according to the movement authority indicated by the signal light. The equipment used in the ETCS level 1 is shown in the **Figure B.2**. The track is divided as blocks equipped with track circuit for checking the presence of a train in any block.

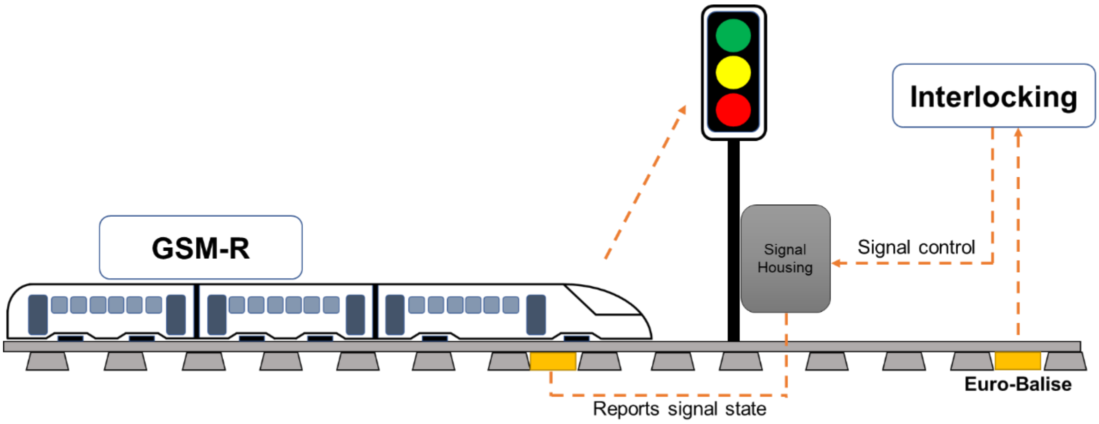

Figure B.2 ETCS level 1 (modified from THALES (2019))

The blocking time theory is used to control trains proceeding on the same route safely. When the specific block section is occupied by a train. The other trains are blocked to access to the block section (Hansen & Pachl, 2014). The length of block depends on the number of signal aspects, and the absolute braking distance of the fastest train operating along the route. The national ATP is replaced by the full function of ATP that will apply the emergency brake if the current velocity of the train is higher than the permissible velocity (Havryliuk, 2017). The electrical signal unit (track circuit and axle counter) continuously checks the present of a train and translate to the light signal as a movement authority.

The movement authority in terms of signal status, block length, and velocity limit is transmitted to the Euro-balise. Once a train passed the specific balise, it receives the information and will use the information to calculate the maximum permissible velocity and then create its velocity profile. In each time that a train passes the next balise, it receives the movement authority extension in which the train can proceed to the next section without stopping. If no movement authority extension is granted, the next braking point is identified, and the braking curve is calculated to ensure that the train can stop without colliding with the train ahead. In this level, the driver is allowed to determine the distance that a train can proceed together with the movement authority extension received when passing the Euro-balise.

2. ETCS level 2

The ETCS Level 2 is a radio-based system that does not require lineside signal, but it still require the train detection equipment such as Euro-balise which is used to detect the current position of a train. The trains can directly communicate with the Radio Block Center (RBC). Once a train passes the balise, the current position of a specific train is detected and sent to the RBC. Thus, the RBC knows the current position of all trains operating within the control area. The RBC then determines the new MA sending back to the train. After that, the onboard computer on the train calculates the velocity profile and identifies the next braking point of a train (THALES, 2019).

To ensure safe traveling, the onboard computer continuously receives its current position for checking whether its operating velocity is accorded to the distance travelled. In the case that a train operates by velocity higher than velocity limit, the ATP system will warn the driver to decelerate. If the driver does not respond to the warning, the emergency brake system will be applied.

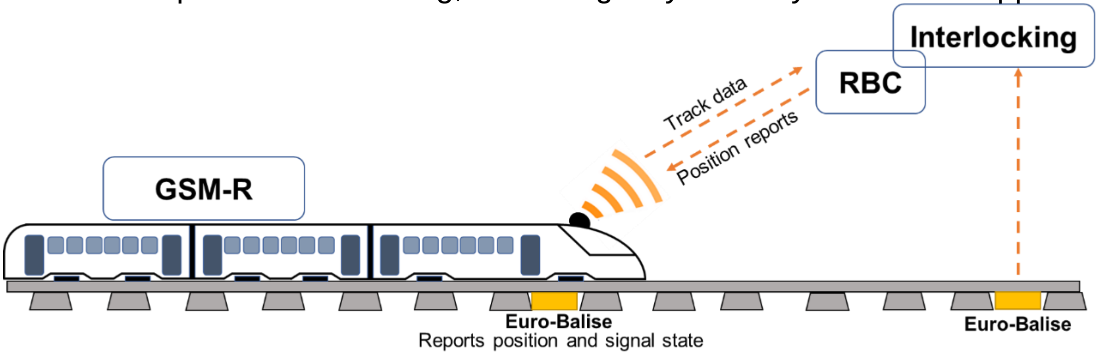

Figure B.3 ETCS level 2 (modified from THALES (2019))

3. ETCS level 3

Similar to the ETCS level 2, the onboard computer installed in the train is allowed to communicate with the control centre (**Figure B.4**). The track is not divided as the fixed block section but divided into the moving section (Ramdas et al., 2010). This level is so called “Moving Block Signalling, MBS”. The trackside and train detection equipment can be eliminated reducing the cost of system construction and maintenance. A train continuously reports its current position and velocity to the control centre. The control centre receives the position of all trains within the control area and then uses the information to determine the movement authority sending back to the trains. The velocity profile is real-time created by the onboard computer using the movement authority from the control centre (Haramina, Brabec, & Grgic, 2012). In which the track is not divided as the fixed block, the optimal velocity that a train could operate relies on the position of a train in front. As a result, a train could run closer to each other increasing the route capacity. This system is suitable for using in the route that trains operate with same stopping pattern, proceed with the same velocity, and have similar performance characteristic (Harriss, 2016).

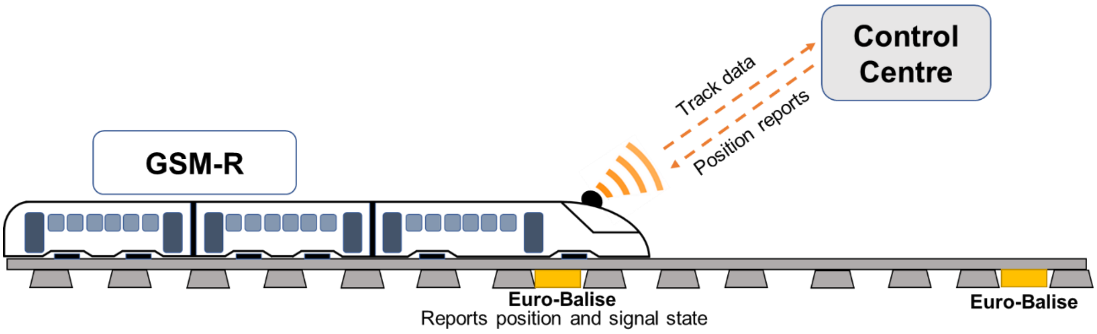

Figure B.4 ETCS level 3 (modified from THALES (2019))

The ETCS Level 3 can be considered as a safe controlling system relying on the safe separation distance between successive trains. It means that the following train can achieve a full stop without collision with its front train. It can be demonstrated that controlling trains under the ETCS Level 3 can increase route's capacity and reduce delay (H Takeuchi, C.J Goodman, & S Sone, 2003). Compared to the ETCS Level 1 and 2, the ETCS level 3 also has higher reliability, flexible and automated operation in e.g. train timetable recovery and junction management (Mirse, 2018).

4. ETCS level 4

When a train follows each other on the same route, it could move like a single train by accelerating or braking accorded to the movement of the train ahead. It could operate as such a situation if it knows the information of its front train. Let's imagine when a train applies brake, it not suddenly stops but continue to move forward. If it is separated from a train behind by absolute braking distance (the distance required for the ETCS level 3), the distance between successive trains when they stop is too long limiting the route capacity. Basically, the trains could run closer to each other based on the assumption that a train does not stop dead after applying brake. As the development of communication system that allows trains to communicate, send and receive an information between them, the following trains can calculate their MA by themselves using their current velocity, position, and route data sent from the train running in front (**Figure B.5**).

Two successive trains are separated by the relative braking distance that relies on the relative velocities of any successive trains, braking ability of the following train, and safety margin due to communication delay, an error of train position detection and driver response time. Before merging the trains into convoy, trains are running under MBS and receive the MA from the control centre. The following train can merge itself into the same convoy with the train in front by sending the merging proposal to its leader.

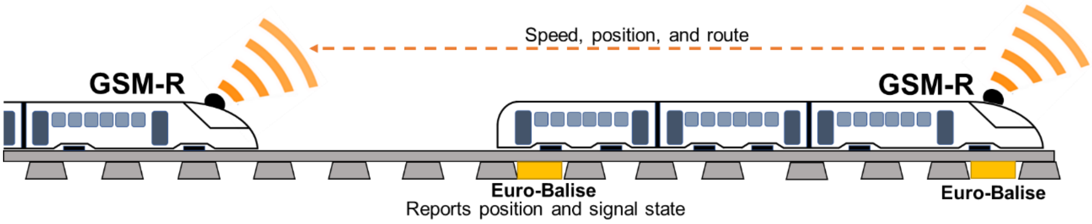

Figure B.5 ETCS level 4 (Modified from Mitchell (2016))

In the case of emergency that the communication between trains controlled by VCS fails to operate, the system will be switched back to MBS and all trains will be controlled by MBS in which the separation distance between trains must not be less than the absolute braking distance.

Appendix C
Updating position and velocity of a train

Updated velocity

$$v_k(t+\Delta t) = v_k(t) + a_k^{opt}(\Delta t)$$

Updated position

$$x_k(t+\Delta t) = x_k(t) + \left[v_k(t)(\Delta t) + \frac{1}{2}a_k^{opt}(t)\,(\Delta t^2)\right]$$

where

$\Delta x_k(t)$	is the separation distance between a leading train k and a following train k+1 at time t $\Delta x_k(t) = x_k(t) - x_{k+1}(t)$
$x_k(t)$	is the position of a leading train k at time t
$x_{k+1}(t)$	is the position of a following train k+1 at time t
Δt	is the communication time between successive trains k and k+1
$v_{k+1}(t)$	is current velocity of a following train k+1 at time t
$a_{k+1}^{opt}(t)$	is the optimal acceleration rate for a following train k+1 at time t