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Article

The Conditions and Suitable Coupling Speed to Create a Train Convoy: A Train Movement under the Virtual Coupling Control

Naphat Ketphat[1,a] **and Somchai Pathomsiri**[2,b,*]

1 The Cluster of Logistics and Railway Engineering, Faculty of Engineering, Mahidol University, Thailand
2 Department of Civil and Environmental Engineering, Faculty of Engineering, Mahidol University, Thailand
E-mail: [a]naphat.kep@mahidol.ac.th, [b,*]somchai.pat@mahidol.ac.th (Corresponding author)

Abstract. A new signaling control called "Virtual Coupling System" (VCS) has been developed and proposed for increasing rail line capacity without construction of new lines. Coupling trains proceeding as a train convoy increases the headway (time space) in front of the convoy. Receiving the benefit from an increase in headway, more trains can be inserted to proceed along the same line increasing capacity. However, it is not clear when trains should be coupled as a train convoy and how a train convoy is built.

In this article, the objective is to provide the conditions to determine whether a train convoy should be built, conditions to determine the number of trains that should be coupled into the same convoy, and the equations to calculate the suitable speed that trains should proceed for coupling into the train convoy. According to the simulated train movement based on the proposed approach, the line capacity is significantly increased as an additional train can be inserted. The headway in front of a train convoy is increased allowing an additional train to be inserted into the same line. In addition, it is ensured that trains can proceed as a train convoy safely, in which the separation distance between successive trains is longer than the minimum safe distance required for the VCS.

Keywords: Virtual coupling, train convoy, coupling speed, capacity, safety.

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1. Introduction

Among metro lines around the world, the concept of Moving Block Signaling (MBS) is widely applied to control a train's movement. A train must be separated from its front train by at least the absolute braking distance which directly depends on its current speed and its braking capability. The Movement Authority (MA) of a train is continuously updated using current trains' data. It is different from the MA of the trains proceeding under the Fixed Block Signaling (FBS) control, in that the successive trains are separated by the block length.

Based on the operation under the FBS, one block (section) can be occupied by only one train at any one time. Thus, the separation distance or headway between successive trains operating under the MBS is reduced compared to the separation distance under the Fixed Block Signaling (FBS) causing an increase in line capacity [1]. However, due to the increase in passenger demand, the number of train services should be increased for serving the huge number of passengers. There are many ways to increase capacity such as constructing new lines, balancing of the origin and destination ridership distribution based on land use development [2], or reducing distance between trains operating based on new signalling control. Constructing new lines or balancing of the OD ridership distribution can be considered as the solution to increase line capacity but there are many problems including unavailability of investment funds and limitations of an available construction area. Thus, another solution to increase line capacity is to control trains moving closer and reduce headway between them to provide more time gap to insert more trains operating along the same line.

As such an effective solution which will decrease distance or headway between trains, a new signaling train control called Virtual Coupling System (VCS) is introduced. The idea is to control trains to proceed closer to each other and operate like a car following movement [3]. Controlling train proceeding based on the VCS can decrease the separation distance between successive trains. The distance between trains is shorter compared to the separation distance between trains under both FBS and MBS; therefore, allowing more trains to proceed along the same line.

Train with Virtual Coupling System (VCS), the next generation of railway signaling and train control, has been developed for increasing rail line capacity. The headway between trains is less than the minimum headway required for operating under the FBS and MBS. The difference between the MBS and the VCS systems is architecture and the minimum safe distance between successive trains [4]. The system architecture of MBS and VCS is shown in Fig. 1. Based on the operational control under the MBS, a train's position and speed is continuously sent to the control center via communication system. Then, the control center sends the MA to trains within the control area. A train receives the MA and uses it to generate the speed profile indicating the Supervised Location (SvL) and point of End of Authority (EoA). The successive trains controlled by the MBS are separated by at least the absolute braking distance in Eq. (1) [5] to guarantee safety and ensure that a train can stop safely without collision with a train moving in front. Based on the MBS, the minimum safe distance is the instantaneous braking distance that a following train can stop safely plus a safety margin due to any errors [6].

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

where $V_{k+1}(t)$, b_{k+1}^{max}, and SM refer to real time speed of the following train, its maximum braking rate, and safety margin added into the equation to prevent any error.

The safety margin (SM) is also added into the minimum safe distance's equation to prevent any error caused by the system and communication delay.

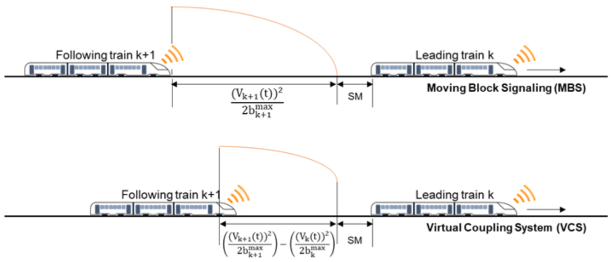

Fig. 1. System architecture of MBS and VCS.

The system architecture of the VCS in terms of technology and functionality are similar to the system architecture of the MBS [1]. Differently, a train will send the train data including position and speed directly to its following train instead for creating the MA and speed profile. Trains can virtually be coupled as a single train relying on the data transferred between them. Communication and data transmission systems have been improved to serve the need of systems for sending and receiving data [8]. The successive trains built as the same train convoy are separated by at least the relative braking distance. The relative braking distance (Eq. (2)) is significantly shorter than the absolute braking distance, the minimum safe distance required for MBS, as it depends on the difference between the leading and the following train's speed. It is noted that the first train in a train convoy still operates under the MBS.

$$\Delta x_{k+1}^{VCS}(t) = \left(\left(\frac{(V_{k+1}(t))^2}{2b_{k+1}^{max}}\right) - \left(\frac{(V_k(t))^2}{2b_k^{max}}\right)\right) + SM \tag{2}$$

Taking the benefit from data transferred directly from the leading the following train, trains can proceed closer and safely. Quaglietta [7] suggested that not only the current speed and position but also the maximum braking rate, and route should be sent to its following train. It should be sent for safety reasons to prevent collisions between trains in the case that a following train brake by using a lower braking rate causing a longer distance required to stop. Thus, it is important to have braking rate information for creating the speed profile accurately. Saxena et al. [9] also recommended that the control strategies and transferred data should be designed based on communication topology. Once the signaling control is switched to the VCS, it can be assumed that the probability that a train stops dead is zero. It can be said that a train does not stop at the point which it begins to stop but can proceed further at deceleration rate; therefore, reducing separation distance away from its following train. When trains proceed as the same train convoy, the following train will adjust its speed in accordance with its leading train speed. Consequently, the rail line capacity is increased compared to the capacity under other signaling controls [4, 9-12].

The researcher envisions the lack of the process to create a train convoy especially in the case that the number of trains exceeds the capacity under MBS. In this paper, the process to create a train convoy is proposed. The conditions to determine the need of VCS, the number of trains built into the same train convoy, and suitable speed for a train coupling into a train convoy are determined. Creating a train convoy with the suitable number of trains and suitable speed will increase line capacity serving an increase in passenger demand.

2. Literature Review on Train with Virtual Coupling System

In some railway lines where the capacity is close to the maximum capacity, adding train services to serve the passenger demand is not possible because there is no time gap to add more trains. Managing trains proceeding closer to each other will be the solution to increase line capacity without construction of additional lines. The Virtual Coupling System (VCS) has been developed mainly in order to increase line capacity by reducing separation distance between trains.

2.1. Coupling Train Operation as a Train Convoy

Currently, there are many approaches proposed to control a group of trains operating as a train convoy. Theories such as car-following model, distance difference model, distance, and speed difference model, etc. have been used to create the following train movement's approach. Car-following model is the one famous model used as theory-based approach for controlling the following train's movement based on the concept that when trains proceed under the VCS, the following train's movement is similar to the following car's movement on highway [13]. Moving based on car-following model may not be well applied to control the following train's movement due to the wider range of acceleration and deceleration rates. An additional term is proposed and included into the car-following equation in order to control the acceleration and deceleration rates to be in the realistic range resulting in good stability [3, 14].

Based on the movement concept under the VCS, in which the separation distance between successive trains is minimized but not less than the minimum safe distance, the concept of distance difference control model is applied. The idea is to control the following train proceeding in accordance with the leading train's movement to maintain the separation distance between them. The line capacity will be increased by coupling trains together and operating them as a single train moving with the same speed for maintaining the separation distance between them. The maximum rail line capacity can be achieved when trains proceed at the same speed [15].

The following train will accelerate when the leading train accelerates, proceed at constant speed if the leading train does not change its speed, and decelerate when the leading train applies brake. It is noted that the following train will accelerate or decelerate at the same rate as the leading train. There are many approaches developed based on this concept such as the approach introduced by [16-18]. These were developed based on the distance difference control law by adjusting the separation distance between successive trains to be close to minimum safe distance required for the VCS.

Not only the separation distance between trains but also the speed difference between them impacts on the movement of the following trains under the VCS [1, 10, 24, 26]. This is because the minimum safe distance required for this signaling control depends on the operating speed of successive trains. Henke et al. [10] proposed the following train's movement approach based on distance and speed difference control laws. The following train will proceed at a higher speed and will maintain the speed difference from the leading train for merging into the same train convoy. When the separated distance from the leading train is close to the minimum safe distance, the speed difference between both trains is reduced for safety reasons. The approach was developed to increase line capacity by modifying the minimum safe distance equation by [25]. The simulated results showed that the distance between trains decreased as compared to the distance obtained from the previous approach. Quaglietta et al. [1] also proposed the following train state movement based on the distance and speed difference control. There are four moving states including coupling, coupled, intentionally splitting, and unintentionally splitting states. When the following train operates under the coupling state, it will proceed at a higher speed to catch up with its leading train. Then, it will be forced to decelerate to the same speed as its front train when the distance from its front train is in the acceptable safe distance, transferring trains into the convoy state. If the distance between trains is increased, the trains will be in the splitting state, and they will operate under the MBS when the distance between them is longer than the minimum safe distance required for MBS. If they are unintentionally spitted out, the following train will be forced to accelerate to catch up with its leading train again. Transferring into the convoy state may lead to an unsafe situation if the distance between trains after being transferred is less than the minimum safe distance. Quaglietta, Wang, and Goverde [19] proposed the estimated optimal transferring point to indicate the point that the following train should decelerate to be transferred into the convoy state. They suggested that the following train should start braking for transferring into the convoy state when it is separated from the leading train by the relative braking distance plus the distance which the following train proceeding to decelerate to the same speed as the leading train. Ketphat et al. [24] also introduced the movement state for controlling a group of trains proceeding as a train convoy. There are six movement states proposed to control the following train's movement, and the minimum safe distance equation is modified to improve safety. According to their simulation results, trains can be coupled into the same train convoy safely. In addition, the following train's movement is stable avoiding stop and go movement.

2.2. The Conditions to Build a Train Convoy

The line capacity will not be increased by coupling trains together into a train convoy if the number of trains proceeding on the same line is not increased. Thus, it is important to determine when the VCS is applied, how many and which trains will be coupled together into the same train convoy, and the suitable speed a train proceeding for coupled into a train convoy. The factors determined to build a train convoy are summarized in Table 1.

Although some approaches for controlling trains under the VCS have been proposed [13, 14, 17, 21], it is not exactly clear when the VCS should be applied for building a train convoy. According to the train's movement approach introduced by Quaglietta and Goverde [1], the signaling control will be switched to the VCS when the following train is catching up with its front train and the distance between them becomes lower than minimum safe distance under the MBS. It is noted that the VCS will be used only in the case that both trains proceed along the same line.

Currently, there are several approaches proposed as an effective model for controlling trains under the VCS. Most of them are simulated using only two trains built into the same train convoy [1, 12, 14, 17, 20, 21, 22].

Table 1. Factors determined to build a train convoy.

Factors	Authors	Result
When then VCS is applied	Quaglietta and Goverde [1]	The VCS will be applied when the following train's speed is higher than its leading train and the distance between trains is lower than minimum safe distance under the MBS.
	Mitchell [11]	The VCS will be applied when the trains operating along the same line exceeds capacity under the ETCS level 3 (MBS).
No. of trains	Chen et al. [23]	Two trains had been coupled to prove the effectiveness of the proposed approach. However, there are no conditions for determining how many trains should be merged into the same train convoy
	Ye and Li [12]	Only two trains are built into a train convoy.
	Ketphat et al. [20]	No conditions to determine how many trains built into the same convoy. Two trains had been coupled for proving the approach
Coupling speed	Henke and Trachtler [25]	Trains were built into the train convoy by using fixed speed difference.
	Pan and Zheng [27]	Acceleration rate depends on both velocity and distance difference.
	Duan et [26]	A following train has operated by a higher speed (maximum allowed speed) than its leader until the separation distance between them is equal to or shorter than the minimum safe distance.
	Chen et al. [28]	They provide the approach to limit speed to protect over speed movement.

According to Quaglietta and Goverde [1]'s approach, the train that will be merged into a train convoy is not fixed. It is a train separated from its front train by a shorter distance than the minimum safe distance. The approach proposed by Chen et al. [23] simulated more than two trains to prove the effectiveness to control a train convoy and to prevent overspeed. However, there are no conditions for determining how many trains should be merged into the same train convoy.

Trains may not be built into the same train convoy due to the limitation of distance between stations or any conflict points. In other words, trains may not be coupled into the same train convoy if they are coupled by using low speed difference. According to previous approaches such as the approach introduced by [25], trains are built into the train convoy by using fixed speed difference. The coupling speed of both trains does not rely on the coupling distance (the distance that trains proceed for merging into the train convoy). In many previous studies such as the studies by [1, 26, 28], the suitable speed of trains built into a train convoy is not determined. The following train will accelerate to the top speed, speed limit, for coupled into a train convoy. Thus, it can be said that there is currently no study focusing on the suitable coupling speed or the suitable speed that trains should proceed for merging as a train convoy.

3. Conditions and Analysis of Train with Virtual Coupling System

The operational concept of the VCS is to manage a group of trains moving closer to each other reducing the separation distance between them. Based on the VCS, trains are coupled as a train convoy (Fig. 2) forcing the following trains k+1, and k+2 to move in accordance with its leading train k. The separation distance between trains is at least the relative braking distance depending on the operating speed of both trains.

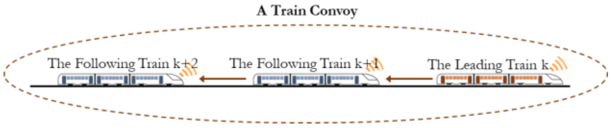

Fig. 2. The train convoy.

3.1. Proceeding under the VCS

In this article, the operational state movement under the VCS introduced by [24] (Fig. 3) is used for determining the conditions and developing equations to create the train convoy. The conditions (speed and distance difference) of each state are shown in Table 2.

Referring to the proposed operational states shown in Fig. 3 and Table 2, the approach is based on the speed and distance difference which begins with the coupling state (State 3) where the following train k+1 proceeds at a higher speed than the leading train k. As a result, the distance between trains becomes closer to the minimum safe distance (State 6). Then, the following train k+1 will be forced to decelerate by b_{k+1}^{opt} to the same speed as the leading train k when the separation distance between them is within the range of minimum safe distance.

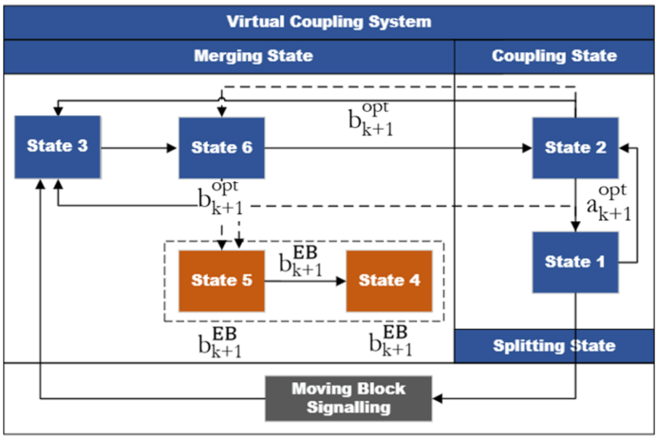

Fig. 3. The movement states under the virtual coupling system.

After that, trains will be operated under the VCS as a train convoy (State 2 or convoy state), in which the following train will adjust its speed to be equal to its leading train for maintaining the distance separated from its leading train. During the convoy state, the following train will accelerate by using the suitable acceleration (a_{k+1}^{opt}) and deceleration (b_{k+1}^{opt}) rates shown in Table 2 [24].

The following train does not apply emergency brake (b_{k+1}^{EB}) in the case that the distance separated from the leading train is less than the minimum safe distance, but its operating speed is lower than (State 4) or equal to the leading train's speed (State 5). In our proposed approach, the following trains will be forced to apply emergency stops in any unsafe situations (State 4 and State 5). The following train can split out from a train convoy by proceeding at a lower speed than its leading train to extend the distance separated from its leading train. The signaling system will be switched from the VCS to the MBS when the separation distance between trains is longer than the minimum safe distance for the MBS.

Table 2. Movement States of the Following Train Operating under the VCS.

State Movement	Distance Difference	Speed Difference	Acc Dec
1. Splitting	$\Delta x_{k+1}(t) > \Delta x_{k+1}^{mvc}(t)$	$V_k(t) > V_{k+1}(t)$	a_{k+1}^{opt}
2. Convoy	$\Delta x_{k+1}(t) > \Delta x_{k+1}^{mvc}(t)$	$V_k(t) = V_{k+1}(t)$	0
3. Coupling	$\Delta x_{k+1}(t) > \Delta x_{k+1}^{mvc}(t)$	$V_k(t) < V_{k+1}(t)$	0
4. Splitting	$\Delta x_{k+1}(t) \le \Delta x_{k+1}^{mvc}(t)$	$V_k(t) > V_{k+1}(t)$	b_{k+1}^{EB}
5. Transfer	$\Delta x_{k+1}(t) \le \Delta x_{k+1}^{mvc}(t)$	$V_k(t) = V_{k+1}(t)$	b_{k+1}^{EB}
6. Transfer	$\Delta x_{k+1}(t) \le \Delta x_{k+1}^{mvc}(t)$	$V_k(t) < V_{k+1}(t)$	b_{k+1}^{opt}

* The moving state that the following train is forced to apply EB.

* The speed and position of the following train are updated using the equation below.

$$v_{k+1}(t+\Delta t) = v_{k+1}(t) + a_{k+1}^{opt}(\Delta t)$$

$$x_{k+1}(t+\Delta t) = x_{k+1}(t) + \left[v_{k+1}(t)(\Delta t) + \frac{1}{2} a_{k+1}^{opt}(t)\,(\Delta t^2) \right]$$

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The acceleration and deceleration (braking rate) when moving under the VCS can be calculated by Eq. (3) and Eq. (4) respectively.

$$a_{k+1}^{opt} = \min\left[a_{k+1}^{max}, \frac{(V_k(t) - V_{k+1}(t))}{\Delta t}\right] \quad (3)$$

$$b_{k+1}^{opt} = \min\left[b_{k+1}^{max}, \frac{(V_{k+1}(t) - V_k(t))}{\Delta t}\right] \quad (4)$$

3.2. The Process to Create a Train Convoy under VCS

To create the conditions to build a train convoy, three parameters are identified. The first parameter is the number of additional trains which will be inserted into the timetable. This parameter is determined in order to calculate the headway between an inserted train and any trains in the timetable. Then, the involved trains or the number of trains that will be built into the same train convoy will be identified. The third parameter is the suitable coupling speed of the involved trains. The equations for calculating the suitable coupling speed for a train that will be coupled into the train convoy are introduced.

3.2.1. Existing timetable and the actual headway

The existing timetable refers to the timetable when there are no additional trains inserted into it. The target speed (V_k^{trg}) or the speed that a train proceeds along the line based on the existing timetable, departure time (DT_k) and expected arrival time (ET_k) at the next station can be defined. In the case that an additional train is inserted, the headway between the inserted train and its front and following train (the actual headway, ΔT^{TT}) can be calculated and compared to the allowable headway under the MBS for determining whether a train convoy should be built.

3.2.2. Minimum headway under the MBS

Minimum headway between trains operating under the MBS (ΔT^{mmb}) is required for determining which trains should be coupled into a train convoy. The train operation mode will be transferred to the VCS when the headway between successive trains is lower than minimum headway required for the MBS ($\Delta T^{mmb}(t)$). The minimum headway between successive trains operating under the MB is calculated by using Eq. (5).

$$\Delta T_{k+1}^{mmb}(t) = \frac{\Delta x_{k+1}^{mmb}(t)}{V_{k+1}(t)} \quad (5)$$

where $\Delta x^{mmb}(t)$ is the absolute braking distance or the minimum separation distance between successive trains which can be calculated by $\frac{v_{k+1}^2(t)}{2b_{k+1}^{max}} + SM$. $V_{k+1}(t)$ and b_{k+1}^{max} are the operating speed and maximum braking rate of the following train, respectively. SM refers to the safety margin added due to the communication and system operation delay.

3.2.3. Minimum headway under the VCS

The minimum headway between trains under the VCS or the relative braking distance can be expressed by Eq. (6).

$$\Delta T_{k+1}^{mvc}(t) = \frac{\Delta x_{k+1}^{mvc}(t)}{V_{k+1}(t)} \quad (6)$$

where $\Delta x_{k+1}^{mvc}(t)$ is the minimum separation distance between trains operating under the VCS. It depends on the operating speed of the leading train, $V_k(t)$ compared to the following train's speed, $V_{k+1}(t)$. The minimum safe distance under the VCS can be calculated by $\Delta x_{k+1}^{mvc}(t) = \frac{v_{k+1}^2(t) - v_k^2(t)}{2b_{k+1}^{max}} + SM$.

3.2.4. Expected headway

The expected headway is the time gap between successive trains when they are coupled into the same train convoy. It is noted that the expected headway must not be less than the minimum headway under the VCS ($\Delta T_{k+1}^{mvc}(t)$) and should be lower than the minimum headway under the MBS ($\Delta T_{k+1}^{mmb}(t)$) as shown in Eq. (7).

$$\Delta T_{k+1}^{mvc}(t) \leq \Delta T_{k+1}^{exh}(t) < \Delta T_{k+1}^{mmb}(t) \quad (7)$$

Note: To prevent splitting state when the train convoy approach the diverging junction or the next station, the expected headway between successive trains in the same convoy should not be less than the minimum headway under the VCS ($\Delta T_{k+1}^{mvc}(t)$) plus dwell time (ΔT_{k+1}^{dwell}) at the next station (Eq. (8)).

$$\Delta T_{k+1}^{exh} = \Delta T_{k+1}^{mvc} + \Delta T_{k+1}^{dwell} \quad (8)$$

3.2.5. Number of train in a convoy

The number of trains (H) that can be coupled into the same train convoy includes the trains that their headway away from the inserted train is not higher than the expected headway (ΔT^{exh}). In addition, another one train is added as the last train in a train convoy (Fig. 4). It is called the reference train which is still operated by its operating speed.

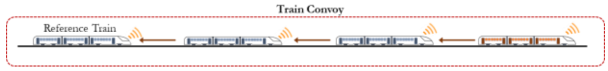


Fig. 4. Reference train in a train convoy

It is also used as the reference speed for calculating the suitable coupling speed for other trains in the same train convoy. Thus, the number of trains which will be coupled into the same train convoy (N) is computed by Eq. (9).

$$N = H + 1 \tag{9}$$

3.2.6. Coupling distance

The merging distance (Δx^{mrg}) in Eq. (10) refers to the distance from the point that a train starts coupling into a train convoy (x^{mrg}) to the expected point that trains are completely coupled into the same train convoy (x^{csp}). Normally, the merging process should be completed before reaching the next station in order to maximize the line capacity.

$$\Delta x^{mrg} = x^{csp} - x^{mrg} \tag{10}$$

3.2.7. Expected extended headway

According to the operating moving state under the virtual coupling shown in Fig. 3, the leading train will operate at a lower speed than the train proceeding behind for allowing the following trains to catch up and to be coupled with it. It is noted that the last train in the convoy (the reference train, see in Section 3.2.5.) should operate at its target speed (based on existing timetable) throughout the merging distance in order to prevent delay impacting on trains following a train convoy. In the case that an inserted train is added into the line, the departure headway between the inserted train and its adjacent trains can be calculated. To insert an additional train into the same line, some trains in the line will be coupled as a train convoy for extending time gap to insert the train.
The expected extended headway (ΔT_k^{ext}) is the difference between the minimum headway under the MBS (ΔT_k^{mmb}) and the actual headway (ΔT_k^{TT}) between the inserted train and the first train in the train convoy (Eq. (11)).

$$\Delta T_k^{ext} = \Delta T_k^{mmb} - \Delta T_k^{TT} \tag{11}$$

The expected extended headway can be calculated in terms of extended distance after forming a train convoy. Thus, the expected extended distance (Δx_k^{ext}) can be estimated using Eq. (12).

$$\Delta x_k^{ext} = \left(\Delta T_k^{exh} - \Delta T_k^{TT}\right) \times V_k^{trg} \tag{12}$$

3.2.8. Suitable coupling speed equation

The suitable coupling speed for the trains in the same train convoy can be calculated depending on the expected headway (ΔT^{exh}) between the inserted train m and its successive trains operating on the main line and the merging distance (Δx^{mer}). Assuming that the first train will start merged into the train convoy when it reaches the merging point (x^{mrg}). As it decelerates and proceeds at a lower speed than its target speed (V_k^{trg}), the distance in front of the first train in a train convoy is increased. Thus, the total time that the first train operated by the suitable merging speed to obtain the expected extended distance can be estimated by Eq. (13).

$$\Delta T_k^{mrg} = \frac{\Delta x_k^{ext}}{\left(V_k^{trg} - V_k^{mrg}\right)} \tag{13}$$

The total time that the first train operated along the merging distance is $\Delta T_k^{mrg} = \Delta x_k^{mrg} / V_k^{mrg}$. By placing this term into Eq. (13), the suitable coupling speed of the first train in the train convoy can be calculated by Eq. (14).

$$V_k^{mrg} = V_k^{trg} \Big/ \left(1 + \left(\frac{\Delta x_k^{ext}}{\Delta x_k^{mrg}}\right)\right) \tag{14}$$

In the case that more than two trains will be coupled into the same train convoy, the suitable coupling speed of the middle train can be calculated by

$$V_{k+1}^{mrg} = \max\left[\left(V_k^{mrg} + \Delta V^{dmrg}\right), V_N^{trg}\right] \tag{15}$$

where ΔV^{dmrg} refers to the suitable coupling speed difference between two successive trains estimated by $\Delta V^{dmrg} = \frac{\left(V_N^{trg} - V_k^{mrg}\right)}{H}$ and V_N^{trg} is the target speed of the last train in the train convoy. It is noted that the V_N^{trg} is the suitable operating speed of the reference train.

3.3. Train Coupling Conditions

The multiple stages in Fig. 5 show the process to create a new timetable in the case that any extra trains are inserted exceeding the capacity under the MBS. The proposed stage model development is performed by adding parameters which will be applied for creating a train convoy. It begins with the determination of whether an additional train can be inserted. The actual headway (ΔT^{TT}) between the inserted train and its adjacent trains is calculated. If the headway is equal to or higher than the allowable headway under the MBS, the inserted train can be inserted safely, and the other trains can be operated based on their existing timetable. Otherwise, the timetable should be rescheduled by merging some trains operating as the train convoy. Then, the expected headway (ΔT^{exh}) is determined. It should be at least the minimum headway allowing for the VC operation (ΔT^{mvc}) plus the dwell time of the next station (ΔT^{dwell}) for preventing splitting state which may affect the operation of trains following the train convoy. Next, the number of trains (N) which will be coupled as the same train convoy is determined. After that, the expected extended headway (ΔT^{ext}) is calculated for determining the extra time gap needed for inserting the train into the same line. Then, the suitable coupling speed (V^{mrg}) for each train which will be coupled into the same train convoy is calculated. Based on the proposed conditions and equations, departure time of some trains may be adjusted, and they will be coupled to operate as the train convoy for increasing time gap to insert more trains operating along the same line.

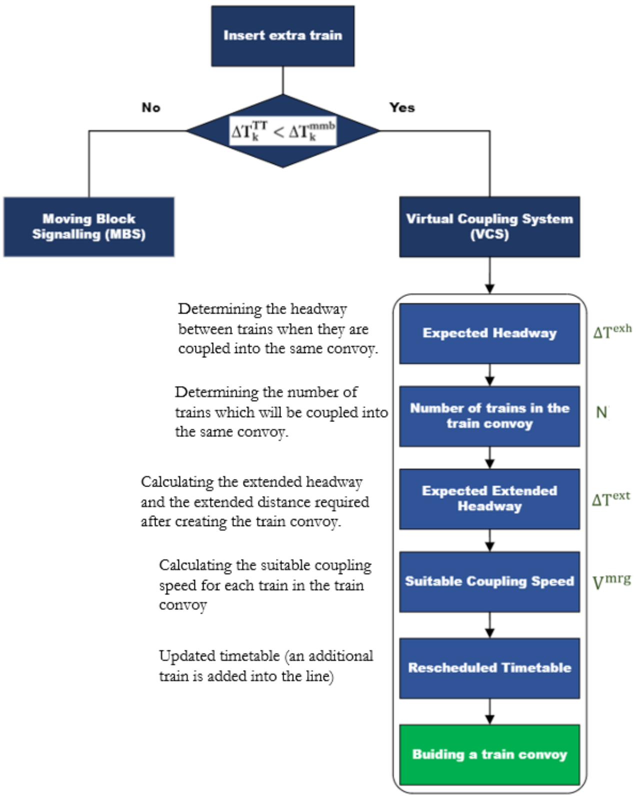


Fig. 5. The process to create a train convoy.

4. Simulation Results

In this part, the train timetable will be managed based on the proposed conditions and equations to create the train convoy by means of simulation technique.

4.1. Train Parameters

Suppose that there are 6 trains proceeding from station A to station B with the departure time shown in Table 3. The current headway under the MBS is 3 minutes.

Assuming that the number of passengers is extremely high than usual, in which 7 trains in normal operation is not enough to carry. Two additional trains, M1 and M2 are being considered to be inserted into the existing timetable. The simulation is to test how the two additional trains M1 and M2 may be inserted to create a train convoy: thereby, increasing the capacity of the rail line. The departure times of trains M1 and M2 are set at 07:02:00 and 07:12:00, respectively. The trains are operated based on the parameters shown in Table 4.

Table 3. Train Timetable.

Train No.	Departure Time	Inserted Train No.	Departure Time
1	07:00:00	M1	07:02:00
2	07:03:00	M2	07:12:00
3	07:06:00		
4	07:09:00		
5	07:12:00		
6	07:15:00		
7	07:18:00		

Table 4. The simulation Parameters.

Parameter		
1) Speed limit (V^{max})	35	m/s.
2) Target Speed (V_k^{trg})	30	m/s.
3) Time step (Δt)	10	Sec.
4) Safety margin (SM)	1500	m.
5) Maximum acceleration rate (a_k^{max})	0.5	m/s²
6) Maximum deceleration rate (b_k^{max})	0.5	m/s²
7) Permissible headway (min. headway) under the MBS	3	min.
8) Permissible headway (min. headway) under the VCS	1	min.
9) Station Length	50	km.

Following the process to create a train convoy in Fig. 5, some trains should be coupled as the train convoy because the headway between the inserted trains and the trains on the old timetable. According to the departure time shown in Table 3, the headway between train 1 and train M1 (ΔT_{M1}^{TT} = 2 minutes), and train M1 and train 2 (ΔT_2^{TT} = 1 minutes) is lower than 3 minutes required for the MBS while the headway from inserted train M1 to train 3 is 4 minutes higher than minimum headway. Following the process to create a train convoy in Fig. 5, train 1, train M1, train 2, and train 3 (reference train) shall be coupled into the same train convoy to increase headway between train 1 and train 2 for inserting train M1.

The headway between train 2 and the inserted train M1 is only 1 minute, but the expected headway between them (ΔT_{M1}^{exh}) is 2 minutes (1 minute is required as the minimum headway under the VC plus 1 minute for station dwell time). Thus, the expected extended headway between train M1 and train 2 (ΔT_2^{ext}) is 1 minutes or 1,800 meters. Assuming that the convoy process is finished at 10 kilometres from station A, the suitable coupling speed of train 2 is $V_2^{mrg} = V_2^{trg}/\left(1+\left(\frac{\Delta x_4^{ext}}{\Delta x_2^{mrg}}\right)\right) = 30/\left(1+\left(\frac{1800}{10000}\right)\right)$ = 25.4 m/s (≈ 25 m/s). Therefore, train 1, train M1, train 2, and train 3 will be coupled into the same train convoy by proceeding at 30 m/s, 30 m/s, 25 m/s, and 30 m/s and depart from station A at 07:00:00, 07:02:00, 07:03:00, and 07:06:00, respectively.

The headway between train 4 and train M2 is 3 minutes which is equal to the minimum headway required for the MBS. Thus, the train 4 can proceed independently. As train 5 and the inserted train M2 will depart from station A at the same time, train 5 shall be coupled into a train convoy with its following trains to increase the headway from the inserted train M2. The train 6 shall be coupled into the same train convoy with the train 5 because the headway from the inserted train is not higher than the minimum headway required for MBS. In addition, train 7 shall be coupled into the convoy as well as a reference train. It is assumed that the inserted train M2 proceeds independently and will not be coupled into any train convoy, an extra 3 minutes or 5,400 meters are required. The suitable coupling speed of the train 5 (first train in the train convoy) is $V_5^{mrg} = V_5^{trg} \Big/ \left(1+\left(\frac{\Delta x_5^{ext}}{\Delta x_5^{mrg}}\right)\right) = 30 \Big/ \left(1+\left(\frac{5400}{10000}\right)\right) = 20$ m/s.

Therefore, train 5, train 6, and train 7 will be coupled into the same train convoy by proceeding at 20 m/s., 25 m/s., and 30 m/s. and depart from station A at 07:12:00, 07:15:00, and 07:18:00, respectively.

4.2. Simulated Train Movement

A following train's movement is simulated based on the proposed approach created using the MATLAB programming. The speed limit of the rail line from station A to B is shown in Fig. 6. A train is allowed to proceed throughout section 1 at 30 m/s. After that, it will decelerate as the speed limit of the section 2 is reduced to 20 m/s. Then, the speed limit is increased to 25 m/s in section 3 before increasing again in section 4. A train will be forced to proceed at 20 m/s approaching Station B.

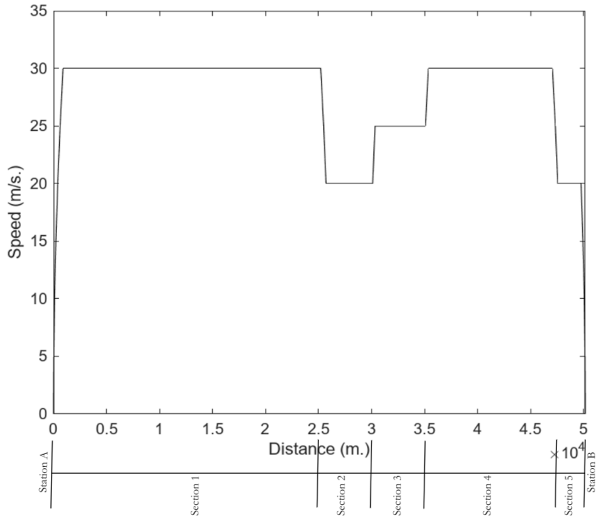
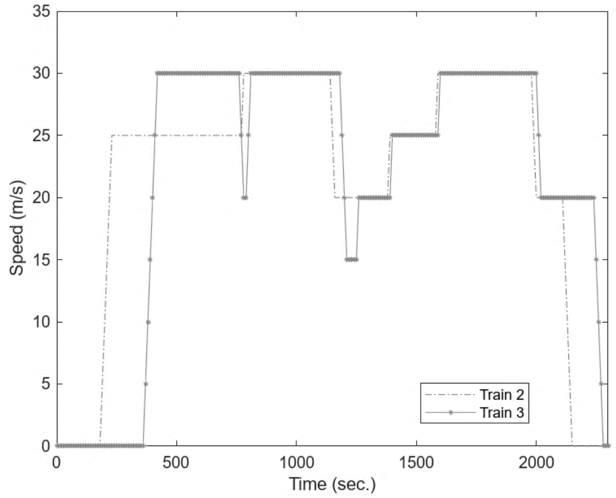
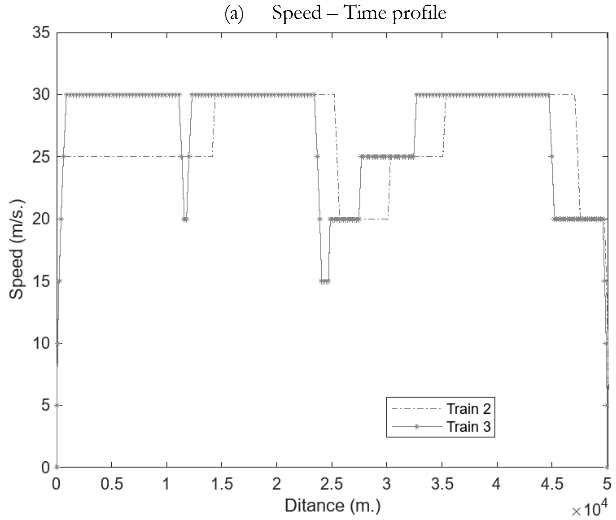


Fig. 6. Section Speed Limit.

As the inserted train M1 is added into the train timetable between train 1 and train 2, the time gap between train 1 and train 2 should be increased allowing train M1 to be inserted into the train line. The headway between trains when arriving at station B is 2 minutes, in which the dwell time of each train is 1 minute.



(a) Speed – Time profile



(b) Speed – Distance profile

Fig. 7. Speed profile of trains in the first train convoy.

Thus, the inserted train M1 and train 1 will be coupled into the same train convoy maintaining 2 minutes headway. However, the headway from inserted train M1 and train 2 is only 1 minute, but at least 2 minutes headway is required. Figure 7 shows the speed profile of train 2 and train 3 which are coupled into the same train convoy for increasing the time gap in front of the convoy. Train 2 proceeds at 25 m/s in the coupling state.

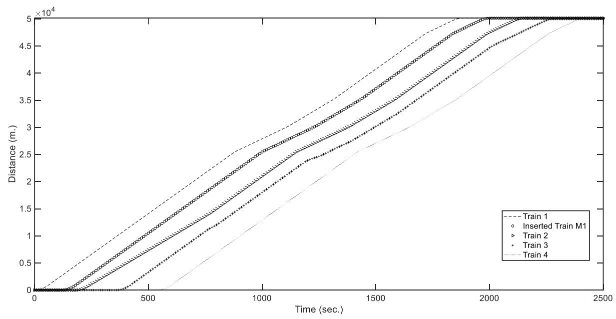


Fig. 8. Distance profile of the inserted train M1 and trains in the first train convoy.

The distance – time profile of the first convoy is shown in Fig. 8. It is seen that the headway between the inserted train M1 and train 2 is increased. The arrival

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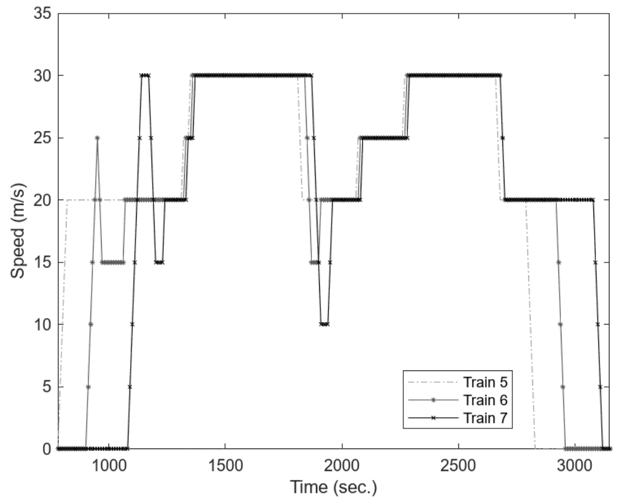
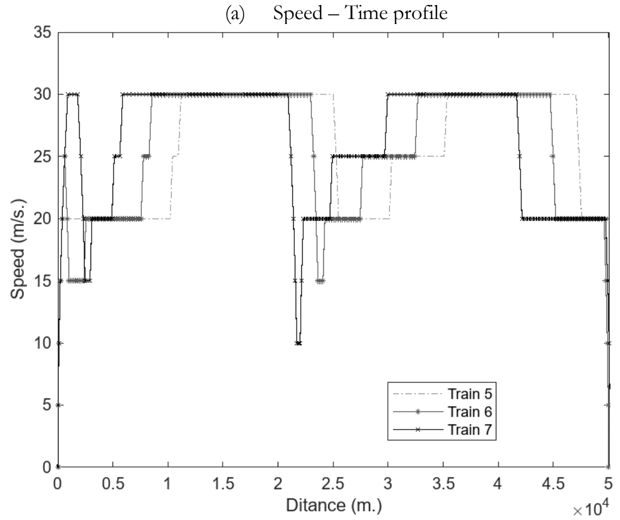
headway between them is extended from 60 seconds to 130 seconds which is slightly higher than expected arrival headway at 120 seconds. This is due to the merging speed of train 2, in which it proceeds at 25 m/s for coupling into the train convoy while the merging speed from the proposed equation is about 25.4 m/s. Train 4 will be coupled into the train convoy in front due to the delay of train 3 that decrease the headway between train 3 and train 4 lowering than the minimum headway required for the MBS.

The inserted train M2 is also added to the timetable between train 4 and train 5. The headway between train 4 and the inserted train M2 is 3 minutes. Thus, they can be operated under the MBS maintaining 3 minutes headway. To add the inserted train M2, train 5, train 6, and train 7 are coupled into the same train convoy to increase time gap in front of the convoy allowing the inserted train M2 to be added into the same line. The speed profile of trains in the second train convoy is shown in Fig. 9. In the merging state, train 5, train 6, and train 7 proceed at 20 m/s, 25 m/s and 30 m/s, respectively.



(a) Speed – Time profile



(b) Speed – Distance profile

Fig. 9. Speed profile of trains in the second train convoy.

The simulated distance-time profile of the inserted train M2 and the trains in the second train convoy is shown in Fig. 10. It is obviously seen that the headway between the inserted train M2 and train 5 is increased from 60 seconds to 210 seconds which is high enough to insert train M2 into the same line safely.

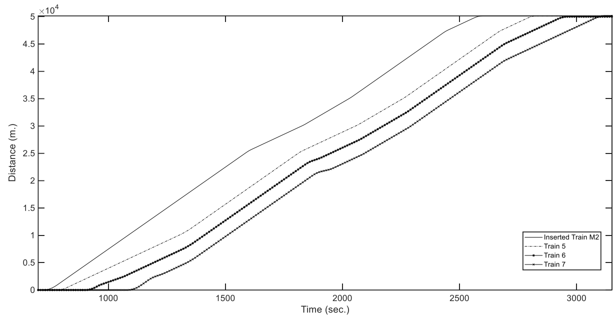


Fig. 10. Distance profile of inserted train M2 and trains in the second train convoy.

The headway between them is equal to the expected extended headway calculated from the proposed equation. Therefore, it is proved that the proposed equation can be applied to estimate coupling speed effectively.

The simulated speed profile of all trains is presented in Fig. 11. To add two extra trains (M1 and M2) into the same line, train 1, inserted train M1, train 2, train 3, and train 4 are coupled into the same train convoy keeping 2 minutes headway when arriving at Station B. The inserted train M2 proceed independently under the MBS as they need to maintain at least 3 minutes from its front train (train 4) and following train (train 5). In the second train convoy, train 5, train 6, and train 7 are coupled together. It is seen that they arrive at station B with 150 seconds (between train 5 and train 6) and 150 seconds (between train 6 and train 7) headway. Thus, it can be concluded that trains can proceed and arrive at the next station safely, in which the headway between successive trains is at least the minimum safe headway.

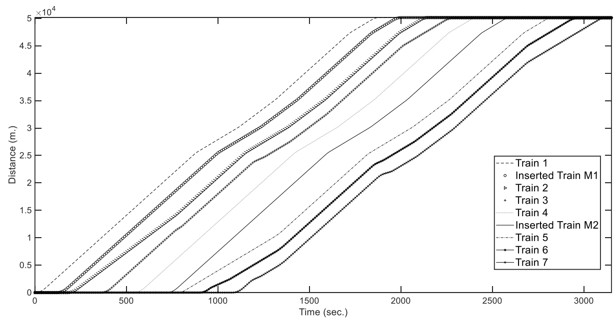


Fig. 11. Distance profiles of all trains.

The departure time, arrival time, and headway between successive trains are summarized in Table 5. It is seen that the headway between successive trains in the same train convoy is not lower than the minimum safe headway of 120 seconds.

Table 5. Departure time, arrival time, and headway.

Train No.	Departure Time	Departure Headway (sec.)	Arrival Time	Arrival Time (sec.)	Arrival Headway (sec.)
1	07:00:00	-	7:31:30	1890	
M1	**07:02:00**	120	7:33:30	2010	120
2	07:03:00	60	7:35:40	2140	130
3	07:06:00	180	7:38:00	2280	140
4	07:09:00	180	7:40:20	2420	140
M2	**07:12:00**	180	7:43:30	2610	190
5	07:12:00	0	7:47:00	2820	210
6	07:15:00	180	7:49:30	2970	150
7	07:18:00	180	7:52:00	3120	150

Table 6 shows travel time and delay of each train. According to the existing timetable, which is no trains inserted, all trains would take 1,890 sec to the next station. The train should arrive at the station B at 07:49:30, but it arrived at 07:52:00 resulting 150 sec delays impacting the departing time of the next train (train 8). Thus, within 18 min (departure duration), the number of trains can be increased from 7 trains to 8 trains (Train 1, M1, 2, 3, 4, M2, 5, 6, and 7).

Table 6. Departure time, arrival time, and headway.

Train No.	Departure Time	Arrival Time	Travel Time (sec.)	Delay (sec.)
1	07:00:00	7:31:30	1,890	-
M1	**07:02:00**	7:33:30	1,890	-
2	07:03:00	7:35:40	1,960	70
3	07:06:00	7:38:00	1,920	30
4	07:09:00	7:40:30	1,890	-
M2	**07:12:00**	7:43:30	1,890	-
5	07:12:00	7:47:00	2,100	210
6	07:15:00	7:49:20	2,060	170
7	07:18:00	7:52:00	2,040	150

It can be concluded that, proceeding under the VCS will increase the line capacity, in which the number of trains proceeding on the same route is increased. In addition, the suitable coupling speed, the merging distance, and the number of trains in the same train convoy can be calculated. Taking the benefit from the proposed equations and flowchart to create a train convoy, the rail line capacity in term of the number of trains in significantly increased.

5. Conclusion

The operational concept of the VCS is to manage a group of trains to move closer to each other; hence, reduce the separation distance between them. Based on the VCS, trains are coupled as a train convoy forcing the following train to move in accordance with its leading train movement. In this paper, the conditions and state movement to merge a group of trains as a train convoy are proposed and analyzed.

According to the simulation results, it is concluded that the rail line capacity is increased as compared to the capacity under the moving block signaling. With the following conditions for creating the train convoy and proceeding by using the suitable coupling speed, the headway in front of the train convoy is increased. It is seen that the extended headway is high enough to insert an additional train; thereby, increasing the capacity of the existing rail line without capital investment on the railway infrastructure. In addition, it could be ensured that trains could be operated safely, in which the separation distance between successive trains in the convoy is longer than the minimum safe distance. VCS has proven to be an inexpensive and attractive solution for increasing railway capacity with no concern about operational safety.

This paper shall be useful for train operation in term of capacity that can be increased by coupling trains as a train convoy. However, the proposed approach is probably effective for long distance between station, in which a following train needs long distance for coupled with its leading train. In addition, it requires the process to split a train from a train convoy when a train convoy approaches a station or passes a diverging junction. The suitable speed and suitable point that a train should start splitting should be determined to receive high capacity at the station.

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Naphat Ketphat received the Ph.D. Degree in Transport Studies from the University of Leeds. UK. After graduated from University of Leeds, she joined Cluster of Logistics and Rail Engineering (CLARE), Faculty of Engineering, Mahidol University, Thailand as a lecturer (In 2022). Her research interests include railway signaling focusing on the train's movement control under the Moving Block Signaling (MBS) and Virtual Coupling System (VCS), railway system safety, railway RAMS, rail transportation, road safety, and road traffic.

Somchai Pathomsiri earned a Ph.D. Degree in civil engineering from the University of Maryland at College Park, USA. He started his career as a transport analyst for a Japanese consulting company in 1988. Few years later, he moved to work for contractors, real estate developer and design companies. Over a decade in the industry, he played major roles in various projects including site engineer, project engineer, project manager and engineering manager. In 1999, he joined Department of Civil Engineering, Faculty of Engineering, Mahidol University, Thailand as a lecturer. He has been teaching courses in transportation, traffic, logistics, supply chain, and engineering management for undergraduate and graduate students at both Mahidol University and others. His research interests include analysis, design, optimization, simulation, planning and management of transportation system and large-scale infrastructure. He has been a recipient of over fifty research and consulting projects granted by both public and private sectors. He is the author of a book, reports, articles in both national and international levels. Currently, he holds the position of associate professor at the department of civil and environmental engineering, Mahidol University. Dr. Pathomsiri is a regular reviewer for several international journals such as Transportation Research, Journal of Transportation Research Record etc. He is a member of The Council of Engineers Thailand holding a senior professional engineer (SPE) license and also a life-time member of the Engineering Institute of Thailand under His Majesty the King's patronage.