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Safety distance control approach in moving block signaling systems

Hareketli blok sinyalizasyon sistemlerinde emniyet mesafesi kontrolü yaklaşımı

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Abstract

As technology progresses in recent years, the advances in transportation continue rapidly. Some of these advances are seen in the railway industry. Especially the innovations in the railway interlocking system make this industry more preferable. One of these innovations is moving block signaling. In an urban rail transport system, moving block signaling has gradually started to replace the fixed block signaling with the development of driverless and communication-based control systems. In this study, an approach has been proposed for moving block signaling. The movement situations between the stations have been shown, by determining a reference speed profile and the relationship between the locations for the following railway vehicles have been evaluated by simulations obtained by MATLAB/Simulink™.

Anahtar kelimeler: Moving block signaling, Communication-based train control, Speed profile, Safe distance

Öz

Son yıllarda teknoloji ilerledikçe, ulaşım sektöründeki ilerleyiş de hızla devam etmektedir. Bu ilerlemelerden bazıları da demiryolu endüstrisinde görülmektedir. Özellikle demiryolu anklaşman sisteminde ortaya çıkan yenilikler bu endüstriyi daha tercih edilir hale getirmektedir. Bu yeniliklerden birisi, hareketli blok sinyalizasyonudur. Şehirlerdeki hafif raylı ulaşım sistemlerinde hareketli blok sinyalizasyonu, sürücüsüz ve haberleşme tabanlı kontrol sistemlerinin gelişmesiyle, yavaş yavaş sabit bloklu sinyalizasyonun yerine geçmeye başlamıştır. Bu çalışmada da, hareketli blok sinyalizasyonu için bir yaklaşım önerilmiştir. Bir referans hız değeri belirlenerek, istasyonlar arasındaki hareket durumları gösterilmiş ve birbirlerini takip eden demiryolu araçları için konumlar arasındaki ilişki değerlendirilmiştir.

Keywords: Hareketli blok sinyalizasyonu, Haberleşme tabanlı tren kontrolü, Hız profili, Emniyetli mesafe

1 Introduction

In the railway industry, signaling systems play a crucial role in ensuring the safe and efficient operation of railway traffic. These systems are essential for regulating train movements, preventing collisions, and optimizing the flow of both passenger and freight transportation. Over the years, various signaling methods have been developed and implemented to enhance railway safety and efficiency. However, certain methods have exhibited limitations in terms of safety, reliability, and adaptability to evolving transportation demands. Consequently, research and development efforts have been continuously pursued to identify and implement more robust and efficient signaling solutions. In particular, advancements in technology, such as artificial intelligence, wireless communication, and real-time data processing, have facilitated the development of innovative signaling methods. These technological improvements not only enhance safety but also contribute to the automation and optimization of railway operations, paving the way for more intelligent and adaptive railway signaling systems in the future.

The development of communication and control technologies has contributed to the advancement of communication-based train control systems. The moving-block signaling system is one of these innovative methods. In the moving block concept, trains move with a certain movement authority received from the control center. In this case, bidirectional communication is used between the trains and the control center to know the position and speed information of the trains.

In the literature, there are some studies about moving block signaling, communication-based train control systems, and automatic train operation. In [1], a Fuzzy control mechanism for the automatic train operation system is proposed, compared with a PID controller, and evaluated the performance of the system. In [2], a tracking algorithm with a fuzzy control system used in metro lines operated with communication-based train control systems is proposed, claiming that the existing basic tracking algorithm is not useful for energy efficiency due to short-term traction-brake cycle and compared this proposed algorithm with the existing algorithm in terms of energy consumption, running time and steady-state interval. In [3], it has been developed a speed profile to minimize energy consumption in a metro line operated with a communication-based train control system with the help of fuzzy logic parameters based on the NSGA-II(Non-Dominated Sorting Genetic Algorithm) method. In [4], for moving block signaling, a cellular

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automaton model is proposed for the simulation of the train movement under mixed traffic conditions, creating a control strategy to reduce energy consumption and examine the dynamic behavior of the train. In [5], a predictive function control method with a complex H_2/H_∞ control approach is proposed to develop the performance of the communication-based train control systems, and a Linear Matrix Inequality approach is proposed to solve the control problem. In [6], two different intelligent train operation algorithms with expert systems and a Reinforcement Learning method are proposed to be used in metro line and compared the difference in energy consumption with an algorithm developed for manual use.

In [7], a nonlinear programming method for automatic train control in moving block signaling, a smoothing algorithm to develop the speed trajectory are proposed and indicated that energy saving and ride comfort are obtained. In [8], a Finite-State Markov Modeling is proposed for wireless channels in tunnel communication-based train control systems and compared with real-time data considering the position information of trains. In [9], Online adaptive PD-based Least Square Support Vector Regression for speed control in moving block signaling is proposed and the results are evaluated considering braking distance and dynamic train equations.

This study presents a novel control approach for dynamically determining the safe distance in moving block signaling systems. While the existing literature mainly focuses on energy efficiency, speed profile optimization, or algorithm performance, this work demonstrates how the safe distance between trains can be calculated over time using physical dynamic modeling. The mass-spring model developed for a four-car train system enables the analysis of motion scenarios in which the movement initiation and speed profile of the following train are optimized based on the position of the leading train. In this respect, the study provides significant contributions to both safety and operational efficiency, particularly for driverless and communication-based train control systems. Furthermore, the proposed approach offers a more application-oriented perspective compared to existing models in the literature, due to its scalability to multi-train scenarios.

In Section 2, information on the methods used in this study is given. In Section 3, simulation results and discussion are given. In Section 4, the conclusion is given.

2 Materials and methods

2.1 Dynamic model of the train

For analysing various train movement scenarios, the single-point train control method is employed as a fundamental approach. This method allows for precise monitoring and regulation of train dynamics at a specific control point, enabling the assessment of factors such as acceleration, deceleration, and stopping accuracy [10-13]. In this control model, a multi-carriage train is considered as a single-point mass and its movement profile is calculated by a Newton equation given in Eq. (1). For this equation, the dynamic model of the train is given in Figure 1. Thus, the formulation of the train movement is given as

$$M\dot{v}(t) = F(t) - B(t) - w(v) - g(x) \tag{1}$$

$$\dot{x}(t) = v \tag{2}$$

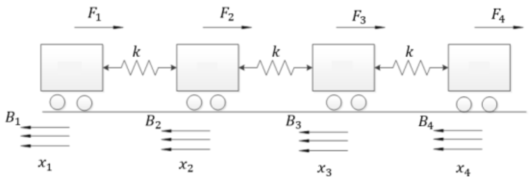

Figure 1. A dynamic model of the train

Where M is the mass of the train, x is the position of the train, v is the speed of the train, t is time, $F(t)$ is the traction force of the train and $B(t)$ is the braking force of the train. Besides, $w(v) = M(c_0 + c_1 v + c_2 v^2)$ is called Davis formula and represents the air resistance and mechanical resistances. $g(x)$ represents the gradient resistance with respect to the position of the train [14].

Therefore, if we consider a train consisting of n vehicles connected by n−1 couplers, the dynamic equations governing the motion of the train can be formulated accordingly. These equations take into account various factors such as the traction and braking forces acting on each vehicle, the resistive forces due to air resistance and track friction, as well as the interactions between the vehicles through the couplers. By incorporating these elements, the mathematical model effectively describes the train's longitudinal dynamics, enabling a detailed analysis of its acceleration, deceleration, and overall motion characteristics. The resulting equations provide a foundation for optimizing train control strategies, improving stability, and enhancing the efficiency of railway operations.

$$\begin{aligned} m_1\ddot{x}_1 &= F_1 - B_1 - k\Delta x_{1,2} - m_1(c_0 + c_1\dot{x}_1 + c_2\dot{x}_1^2) \\ &\quad + R_1^a(x) \\ m_i\ddot{x}_i &= F_i - B_i - k(\Delta x_{i,j+1} - \Delta x_{i-1,j}) \\ &\quad - m_i(c_0 + c_1\dot{x}_i + c_2\dot{x}_i^2) + R_i^a(x) \\ m_n\ddot{x}_n &= F_n - B_n - k\Delta x_{n-1,n} \\ &\quad - m_n(c_0 + c_1\dot{x}_n + c_2\dot{x}_n^2) + R_n^a(x) \end{aligned} \tag{3}$$

Where x_i is position, m_i is the mass, F_i is the traction force and B_i is the braking force of the i-th vehicle. $\Delta x_{i,j+1}$ represents the displacement between i-th and i+1-th vehicle. $R_i^a(x)$ represents the adding resistance force with respect to train position [14].

2.2 Some approaches

In this study, two trains, referred to as Train A and Train B, are considered to be moving in the same direction while following each other within the framework of a moving block signaling system. This system dynamically adjusts the permissible distance between consecutive trains based on real-time operational conditions, enhancing both safety and efficiency in railway traffic management. In this context, Train A is assumed to be the leading train, while Train B is the following train, maintaining a safe separation to prevent collisions. The minimum safe distance between these two trains is determined based on factors such as train speed, braking performance, system response time, and signaling constraints, ensuring that Train B can always decelerate safely without compromising operational efficiency. By this way, if it is assumed that the train A is the leading train and train B is the following train, the minimum safe distance between these trains is

$$d_{min}(t) = d_M + d_{BB}(x_{BN}(t), v_B(t)) \tag{4}$$

In this equation, d_M represents safe margin distance. This is minimum distance value between A and B when both of them stop. d_{BB}, x_{BN} and v_B represent safe braking distance, nose position of train B and velocity of train B. According to the equation, safe braking distance changes with respect to x_{BN} and v_B. However, x_{BN} is ignored generally and d_{BB} only depends on v_B. If d_{BB} is obtained only depends on v_B and deceleration value of train is constant, the equation is given as

$$d_{BB}(v_B) = \frac{v_B^2}{2\beta_S} \tag{5}$$

Where β_S is the deceleration of the train. If the minimum distance equation is rewritten.

$$d_{min}(t) = d_M + \frac{v_B^2}{2\beta_S} \tag{6}$$

By this way, the distance relation between train A and train B is given as

$$d_{min}(t) = x_{AT} - x_{BN} \tag{7}$$

It can be observed that the acceleration of Train B is equal in magnitude but opposite in direction to the deceleration. This indicates that both trains experience the same acceleration, ensuring symmetrical motion dynamics between them. As a result, their kinematic behaviors remain consistent, leading to synchronized motion patterns that maintain balance in their respective speed variations. This characteristic is particularly important in coordinated train control systems, where maintaining uniform acceleration profiles enhances operational efficiency and safety [15].

$$x_{AT} - x_{BN} = d_M + \frac{v_B^2}{2\beta_S} \tag{8}$$

2.3 Movement conditions

x_{AT} stands for the tail position of train A, assuming that $x_{AT}(0) = 0$, is given as

$$x_{AT} = \frac{1}{2}\alpha_A t^2 \tag{9}$$

Where α_A is the acceleration of train A and if it is used as the positive value of deceleration, this value is obtained as $\alpha_A = n\beta_s, n > 0$, [15]. As specified before, in moving block strategy trains move a certain tracking distance. Accordingly, there is a time difference between the following vehicles. Therefore, train B starts to move after Train A takes a certain path. If the time taken by train A is called t_d, train B starts after $t + t_d$ time. In this way, the nose position of train B is obtained as

$$x_{BN} = \frac{1}{2}\alpha_B(t - t_d)^2 \tag{10}$$

If (8) is expressed more clearly, movement condition is obtained as

$$x_{BN}(t - t_d) = \frac{1}{2}n\beta_s t^2 - d_M - \frac{v_B^2(t - t_d)}{2\beta_s} \tag{11}$$

If both sides of (11) are differentiated with respect to t, it is obtained as

$$v_B(t - t_d) = n\beta_s t - \frac{v_B(t - t_d)\alpha_B(t - t_d)}{\beta_s} \tag{12}$$

If the velocity of Train B is expressed as $v_B(t - t_d) = \alpha_B.(t - t_d)$, assuming a constant acceleration α_B, the corresponding relationship is obtained. This formulation implies that Train B follows a linear velocity profile with respect to time, where α_B represents its uniform acceleration. Such an assumption simplifies the dynamic analysis and facilitates further derivations in the context of motion modeling and control.

$$\alpha_B = \frac{n\beta_s^2 t - \beta_s\alpha_B.(t - t_d)}{\alpha_B.(t - t_d)} \tag{13}$$

By this way, α_B is considered as zero when $t < t_d$, where $\alpha_B = -\beta_s$.

It can be observed that the acceleration of Train B is equal in magnitude but opposite in direction to the deceleration of Train A. This symmetry implies that both trains experience identical acceleration characteristics, ensuring a balanced and coordinated motion dynamic between them. As a result, the movement of Train B mirrors the deceleration phase of Train A, maintaining consistency in their respective speed transitions. This property is particularly significant in railway control systems, as it enables smoother train operations, minimizes abrupt changes in motion, and enhances safety by preserving the necessary separation distance between consecutive trains. Furthermore, this symmetrical motion dynamic facilitates precise scheduling, optimizing traffic flow while ensuring adherence to operational constraints.

3 Simulation results and discussion

Simulation results are obtained using MATLAB/Simulink™ by implementing the proposed methodology, and the parameter values utilized in this study are summarized in Table 1 for reference [16,17].

Table 1. Parameters used in the simulation

Parameter	Value	Unit of Measurement
m_1	35000	kg
m_2	30000	kg
m_3	30000	kg
m_4	35000	kg
k_1	300000	N/m
k_2	300000	N/m
k_3	300000	N/m
c_0	8.202	kN
c_1	0.10656	kNs/m
c_2	0.01193	kNs^2/m^2
l_A	60	m
l_B	60	m
d_M	20	m

Considering a light rail transport system operating with a maximum speed of 35 m/s and traveling from one station to another within an average duration of 120 seconds, the corresponding speed profile for this system is illustrated in Figure 2. This speed profile serves as a reference for Train A, providing a baseline for analyzing its motion characteristics. Based on this reference, the position and acceleration of Train A over time are depicted in Figure 3 and Figure 4, respectively. These figures enable a comprehensive examination of the train's dynamic behavior, facilitating insights into its velocity transitions, acceleration phases, and overall motion patterns throughout the journey.

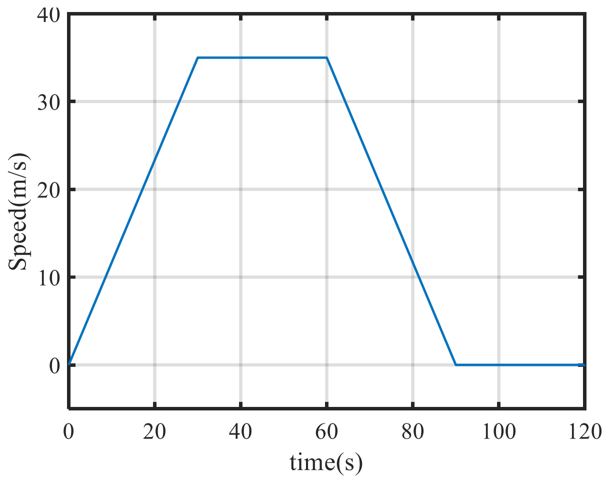

Figure 2. The reference speed profile for train A

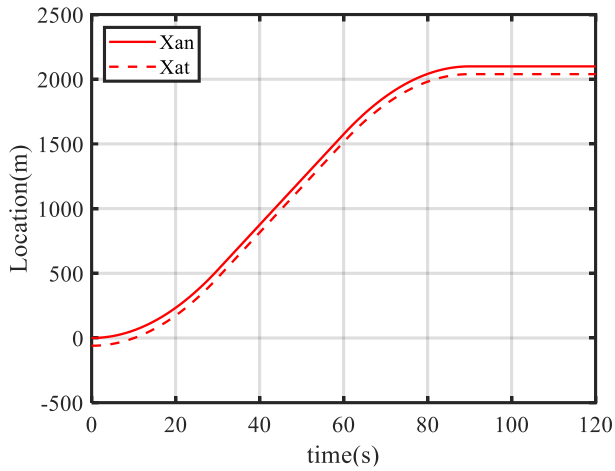

Figure 3. The position of train A with respect to the reference speed profile

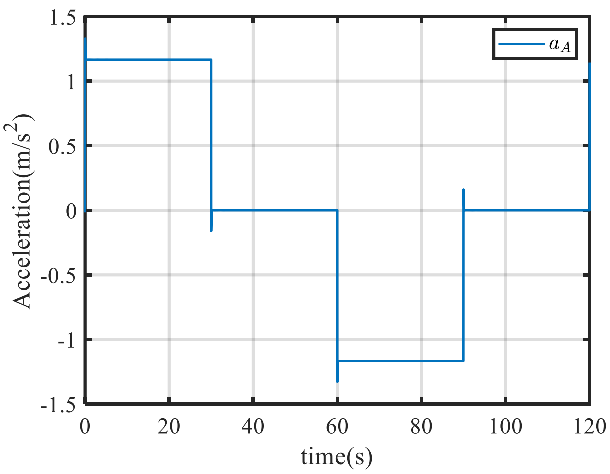

Figure 4. The acceleration of train A with respect to the reference speed profile

The acceleration value derived from the reference speed profile is assigned as the reference acceleration for Train B, as both trains experience the same acceleration under the given conditions. By utilizing this approach, a speed profile is established for Train B, enabling the calculation of the minimum safe distance required between the two trains. However, as evident from the governing equations, Train B does not start moving immediately but instead begins its motion after Train A has traveled a certain distance. This initial gap corresponds approximately to the minimum safe distance, ensuring that Train B can accelerate safely without the risk of collision. To account for this delayed movement, a time delay is introduced into the system, representing the interval before Train B initiates its motion. Based on these defined parameters, the resulting speed profile of Train B, incorporating the time delay effect, is illustrated in Figure 5, providing a clear representation of its velocity evolution over time.

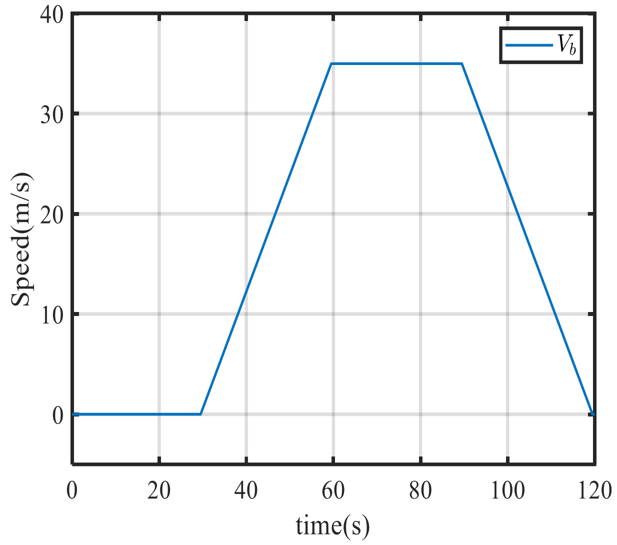

Figure 5. The speed profile of train B

Utilizing this information, a position comparison between the two trains is illustrated in Figure 6, providing insights into their relative movement over time. In this figure, the minimum safe distance, determined from the position values for a speed profile with a maximum velocity of 35 m/s, is calculated to be approximately 527.6 meters. This safe distance ensures that Train B can initiate motion without the risk of a collision while maintaining the necessary separation from Train A. Consequently, Train B begins to move precisely when the tail position of Train A reaches this predefined safe distance. Based on the obtained simulation results, the corresponding time at which Train B starts moving is approximately 29.504 seconds. This analysis highlights the impact of safe distance constraints on train scheduling and movement coordination, contributing to efficient and secure railway operation.

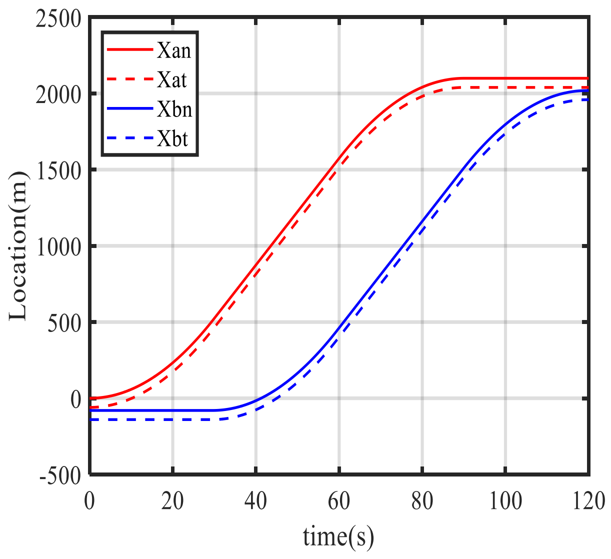

Figure 6. The positions of two trains.

If this approach is applied to a railway system consisting of three stations, the corresponding reference speed profile is illustrated in Figure 7, while the position relationships of the trains with respect to this profile are depicted in Figure 8. These figures provide a clear representation of the trains' motion dynamics, demonstrating how their speed and position evolve over time. As observed from these figures, Train B begins to decelerate precisely at 89.504 seconds. This timing is crucial, as it indicates that the separation distance between Train A and Train B at this moment is approximately equal to the calculated minimum safe distance. Maintaining this safe distance ensures that Train B can decelerate smoothly without violating safety constraints, thereby preventing potential risks of collision while optimizing operational efficiency. The results further validate the effectiveness of the implemented approach in ensuring safe and synchronized train movements across multiple stations.

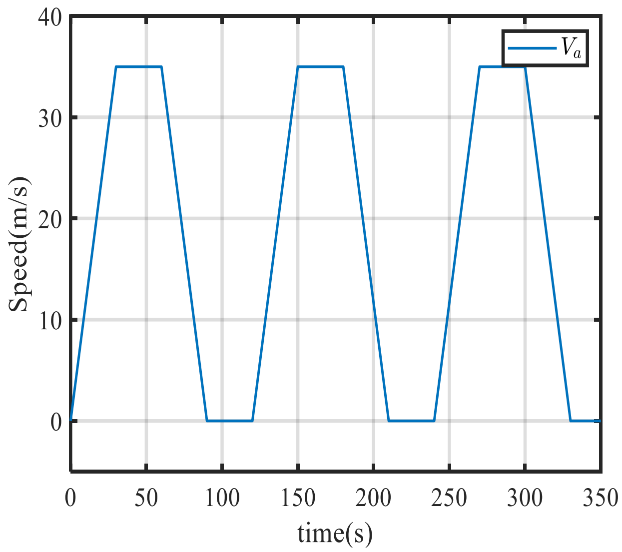

Figure 7. The reference speed profile that represents the movement between three stations

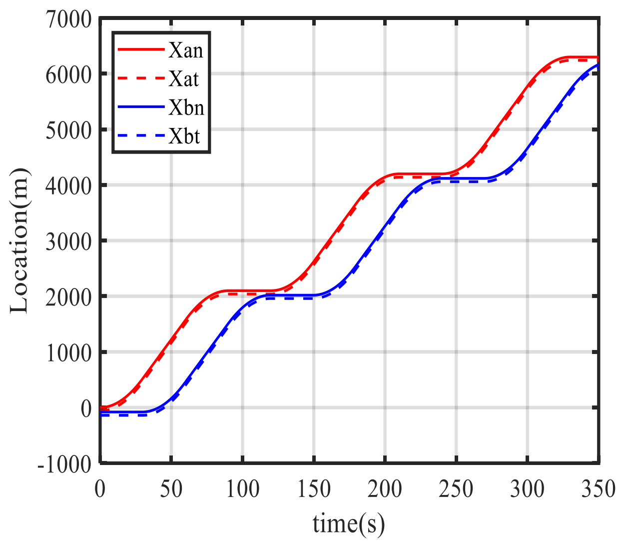

Figure 8. The locations of two trains between three stations

The distance between the two trains at the moment when Train B comes to a complete stop is illustrated in Figure 9. From the figure, it is evident that when Train B stops, the separation distance between Train A and Train B closely approximates d_M, which represents the minimum required safe distance. This observation confirms that the proposed motion control strategy successfully maintains the necessary spacing between the trains throughout their journey, ensuring safe operation within the railway system. The consistency of this distance also highlights the effectiveness of the applied approach in regulating train movements, minimizing the risk of collisions, and optimizing train scheduling efficiency. Furthermore, maintaining this predefined separation is critical for adherence to railway safety standards and operational reliability, particularly in high-density railway networks.

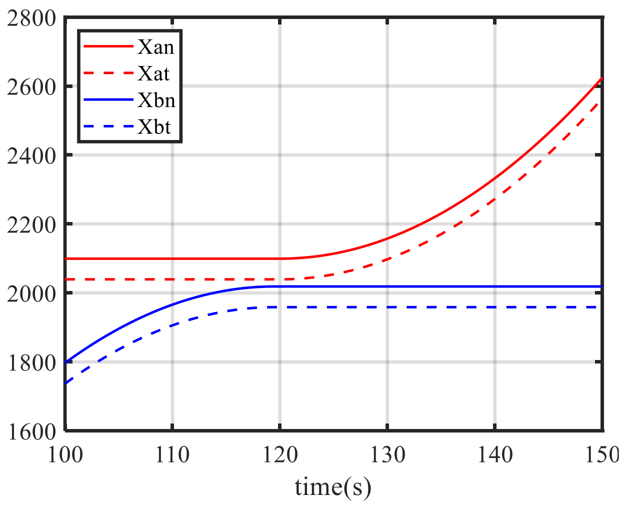

Figure 9. The distance relation between two trains when train B stops.

If this study is extended to a scenario involving three trains following each other, the corresponding position profiles for all three trains are illustrated in Figure 10. Additionally, Table 2 presents the quantitative values of position, speed, and time for the three vehicles, providing a detailed numerical representation of their motion dynamics. In this table, the highlighted values indicate the critical moments when each train begins to move or comes to a stop. For example, at 29.504 seconds, the difference between x_{AT} and x_{BN} is approximately equal to the minimum safe distance, which is computed based on the maximum speed of the following train and the deceleration rate of the preceding train. This confirms that Train B initiates movement precisely at this moment, ensuring a safe and efficient transition. This pattern is consistently followed throughout the system, demonstrating the effectiveness of the applied approach in maintaining safe separation and synchronized motion between multiple trains. The results further validate the methodology's applicability in multi-train operations, optimizing both safety and railway traffic flow.

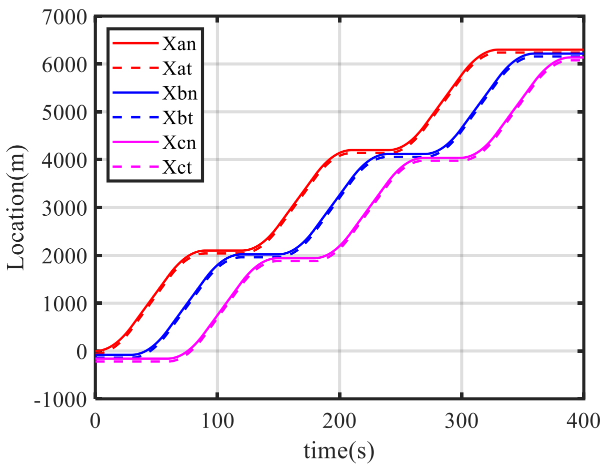

Figure 10. The position relations of three trains

Table 2. Quantitative values

Time(s)	x_{AN} (m)	x_{AT} (m)	x_{BN} (m)	x_{BT} (m)	x_{CN} (m)	x_{CT} (m)
29.504	508	448	-80	-140	-160	-220
59.012	1540	1480	428	368	-160	-220
90	2099	2039	1511	1451	399	339
119.504	2099	2039	2019	1959	1431	1371
149.012	2590	2530	2019	1959	1939	1879
149.504	2607	2547	2019	1959	1939	1879
179.012	3639	3579	2526	2466	1939	1879
210	4199	4139	3610	3550	2498	2438
239.504	4199	4139	4117	4057	3530	3470
269.012	4690	4630	4117	4057	4037	3977
269.504	4706	4646	4117	4057	4037	3977
299.012	5739	5679	4625	4565	4037	3977
330	6298	6238	5709	5649	4597	4537
359.504	6298	6238	6216	6156	5629	5569
389.012	6298	6238	6216	6156	6136	6076

4 Conclusion

In this study, a control approach for moving block signaling is proposed. For this approach, train dynamic model is modelled using mass-spring model, adding rolling stock resistance and rail resistance. This model is obtained ignoring motor dynamics, quarter vehicle model and energy loss and speed profile, acceleration value and position are obtained with a reference speed profile using PID controller.

In the proposed study, for the trains following each other, the following train starts to move with respect to a certain distance covered by the leading train. It means that, the following train starts to move after a certain delay. By this way, acceleration value of the following train is obtained as the negative of the deceleration and this value is given as a reference value to the following train. Then, the speed profile of the following train is obtained and a safe distance value depending on the maximum speed of the following train is calculated. The aim of this approach is to show that the trains transmit the position and speed information by communicating with the radio block centre which calculates the safe distance value according to these data and sends a movement command to the following vehicle according to distance covered by the leading train.

This study is proposed for the trains following each other on the single line and operated with the references. In the future work, new algorithms will be operated considering the movements for the variable speed and position conditions in the railway switch. In addition, the proposed method is planned to be evaluated in comparison with different algorithms and analyzed based on additional performance metrics such as energy consumption.

Conflict of Interest

The authors declare that they have no conflict of interest.

Similarity Rate (iThenticate): 18%

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