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Article

Determining Critical Rail Line Blocks and Minimum Train Headways for Equal and Unequal Block Lengths and Various Train Speed Scenarios

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Abstract. This paper presents a primary model to maximize rail line capacity by minimizing the train headway, defining block time as the time when a train first enters until it leaves the block. The analysis was conducted under a fixed-block system, which allows only a single train to remain in the block. A critical block was identified to determine the minimum safe headway as a function of the train speed, train length, number of trains, and block length. A time–distance diagram was used to analyze operations with equal and unequal block lengths. For two trains operating at the same speed on unequal blocks, the maximum block length defined the minimum headway. For two trains operating at different speeds, a hierarchical analysis was required to identify the minimum headway. Shorter block lengths and a strategic train order affected rail line capacity. The maximum capacity was achieved when two trains operated at the same speed.

Keywords: Block length, headway, capacity, critical block.

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1. Introduction

Thailand's Ministry of Transport recently established a policy to accelerate the development of the rail transportation system in response to the nation's infrastructure problems and in preparation for its participation in the Association of Southeast Asian Nations (ASEAN) Economic Cooperation (AEC) partnership. Approved by a Cabinet resolution, the State Railway of Thailand (SRT) infrastructure investment short-term plan (2010–2015) included double-track projects totalling 873 km for the Northern, Northeastern, and Southern rail lines. The capacity was expected to increase after the implementation of the project; however, the 2010 Master Plan did not specify the prevailing single-track capacity or the anticipated capacity improvement under double-track operation [1].

Unlike road capacity, directly measuring or estimating railway capacity reflecting a rail system's service capability was not possible. Hence, SRT used Scott's formula to evaluate the railway capacity on each line throughout the country based on a speed of 55 km/h reflecting the slowest operating freight train. In reality, mixed types of trains operate on the rail lines with various speeds. SRT's analysis based on the lowest train speed greatly underestimated rail line capacity.

Prior studies on train scheduling attempted to maximize the number of trains by considering operational solutions for a single-track railway system [2, 3] determining the optimal running time, minimum headway, and capacity on a block length basis [4-6] for trains operating with the same speed [7] and different speeds [8-10] and using blocking time models [11-13]. Studies on train scheduling and blocking time particularly benefited railway simulation [14]. A focus on, and subsequent modifications to, blocking time addressed problems in many countries [15]. Most prior studies, however, were conducted under equal block length assumptions.

The researcher envisions the importance in developing equations for analyzing capacity under various train speed scenarios. Relevant variables including the block length, train speed, train length, number of blocks, clearing time and release time. The equation yields the results close to real line capacity and provides flexible application according to operating characteristics. It also proposed the concept of determining the minimum time headway based on train and infrastructure characteristics, control system and critical blocks.

This study addressed the effects of train speed, train length, and block length on the minimum headway and determined the critical block length under equal and unequal block length operations. The findings will be used to improve railway operations in Thailand and to support the future determination of minimum headways.

2. Capacity

In the Transit Cooperative Research Program (TCRP) [4] defined rail line capacity as the total number of trains passing a point during rush hour. Limited capacity suggests a weak link or bottleneck on a system that may extend for some distance. For example, a one-directional light rail line may have a 400–600 m weak link. The calculation of line capacity consists of two key factors: (1) separation time adjusted for constraints (e.g., station, junction, and single track) and (2) dwell time at the station. Figure 1 depicts a simplified formulation of line capacity.

$$\boxed{\text{Line capacity}} = \frac{3600}{\boxed{\begin{array}{c}\text{Minimum train}\\ \text{separation time}\end{array}} + \boxed{\begin{array}{c}\text{Maximum station}\\ \text{dwell time}\end{array}}}$$

Fig. 1. Simplified line capacity formulation [4].

Comparatively, Scott's formula determines line capacity using the longest block and is expressed as

$$\text{Line Capacity, C} = 1440/(T + t) \times E \tag{1}$$

where T is the running time of the slowest freight train over the critical block section, t is the block operation time, and E is the efficiency factor.

The International Union of Railways [16] determines line capacity using the reciprocal of average headway between two successive trains as follows:

$$Capacity = \frac{TimePeriod}{MinimumHeadway} \tag{2}$$

For safety reasons, fixed-block operations require that no more than one train be allowed in any block.

The blocking time (T_{BL}) is the total elapsed time in a block section. It comprises the moving time in a block, time spent to clear the train length from the block, and time to clear signal before entering and after leaving the block [17]. Calculation of T_{BL} considers a number of factors as follows [18]:

$$T_{BL} = tfc + wt + \frac{BL}{V} + \frac{l}{V} + rt + ct \tag{3}$$

where BL = Block length (m)
l = Train length (m)
V = Train speeds (m/s)
ct = Clearing time in the block (s)
rt = Release time (s)
wt = Signal watching time (s)
tfc = Signal clearing time (s)

Figure 2 depicts this relationship graphically.

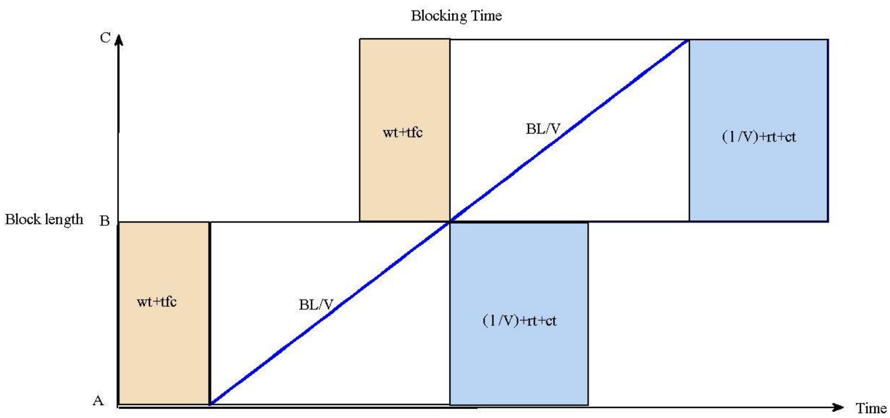

Fig. 2. Blocking time.

3. Analysis

This study's analysis determined the minimum headway in a fixed-block system for two trains traveling in the same direction with cruising speeds of V_i and V_j respectively [19]. Blocking time stairways [17] on a time–distance diagram were used as visualization tools. All blocking times were considered when determining the critical block, which defined the safe minimum headway [20]. Figure 3 illustrates the critical block time determination. In this scenario, the corresponding headway can be calculated for two trains of different types traveling consecutively through a three-block section. The third block in this section is the critical block, which determines the minimum headway.

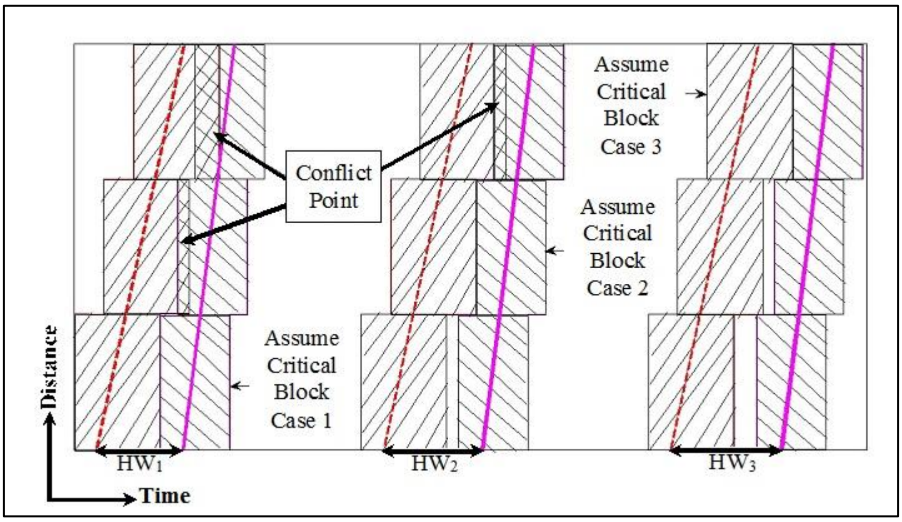

Fig. 3. Critical block determination.

Two operational cases were considered in this analysis: (1) equal block lengths and (2) unequal block lengths. Considering a five-block section, time–distance diagram were constructed for each operational case and for various train speed scenarios including $V_i = V_j$, $V_i > V_j$, and $V_i < V_j$.

3.1. Equal Block Length: $BL_1=BL_2=BL_3=BL_4=BL_5$

Figures 4–6 depict the time–distance diagram for equal train speed (Case 1-1), leading train faster than trailing train (Case 1-2), and trailing train faster than leading train (Case 1-3) under equal block length operations.

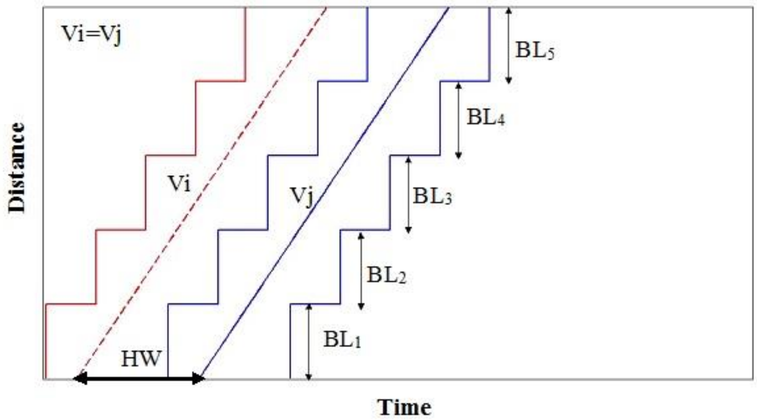

Fig. 4. Time–distance diagram for equal block lengths when $V_i = V_j$ (Case 1-1).

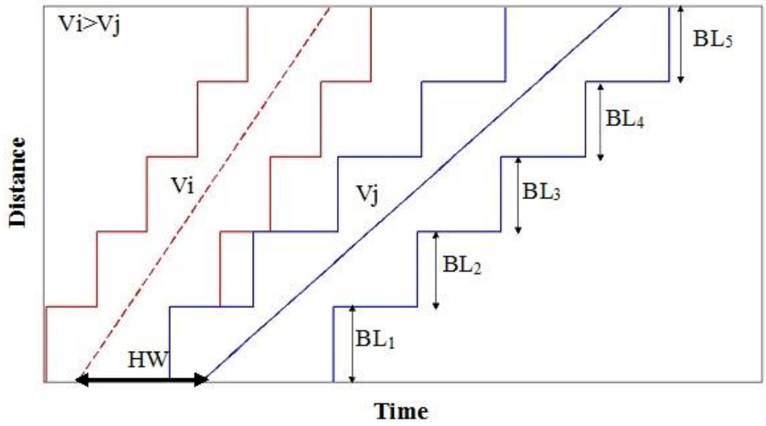

Fig. 5. Time–distance diagram for equal block lengths when Vi > Vj (Case 1-2).

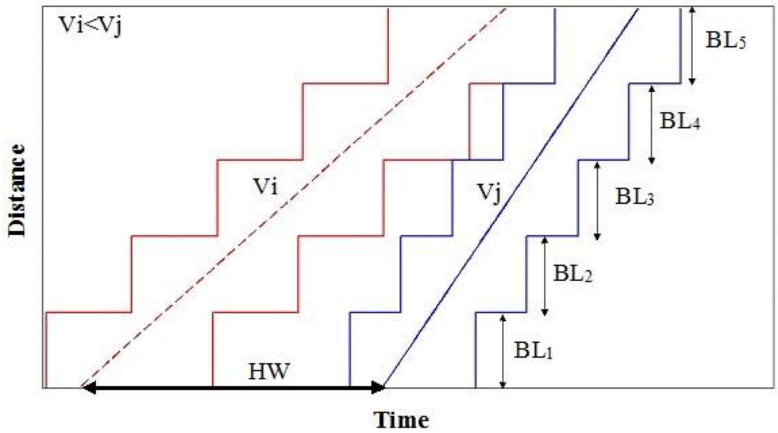

Fig. 6. Time–distance diagram for equal block lengths when Vi < Vj (Case 1-3).

Figures 4 and 5 show that when the train speeds are equal ($V_i = V_j$) or when the leading train is faster ($V_i > V_j$), the trailing train can be released after the leading train has left the block. Therefore, the first block becomes the critical block in determining minimum headway. Figure 6 shows that when the leading train is slower ($V_i < V_j$), the last block becomes the critical block.

In either case ($V_i \geq V_j$ or $V_i < V_j$), headways can be determined as follows:

$$HW = \frac{BL + l}{V_i} + T_{FB} \qquad \text{when } V_i \geq V_j \tag{4}$$

$$HW = \frac{nBL + l}{V_i} - \frac{(n-1)BL}{V_j} + T_{FB} \qquad \text{when } V_i < V_j \tag{5}$$

where n is the number of blocks and $T_{FB} = ct + rt + wt + tfc$.

3.2. Unequal Block Length: $\mathrm{BL}_1 \neq \mathrm{BL}_2 \neq \mathrm{BL}_3 \neq \mathrm{BL}_4 \neq \mathrm{BL}_5$

To construct time–distance diagram for unequal block lengths, the Northeastern Line block lengths from the Muang Phon to Khon Kaen Stations were applied. The section consisted of six stations and five blocks. Table 1 summarizes the block lengths.

Table 1. Block lengths on the northeastern line from Muang Phon to Khon Kaen.

Origin	Destination	Block Length (m)
Muang Phon	Ban Han	19,160
Ban Han	Ban Phai	10,900
Ban Phai	Ban Had	15,880
Ban Had	Tha Phra	16,210
Tha Phra	Khon Kaen	9,940

Figures 7–9 depict the time–distance diagram for equal train speed (Case 2-1), leading train faster than trailing train (Case 2-2), and trailing train faster than leading train (Case 2-3) under unequal block length operations.

Figure 7 shows that when the speeds of the two trains are equal ($V_i = V_j$), the block lengths must not overlap. The longest block length becomes the critical block. The longest block length consists of train clearance time, signal clearing time, signal watching time, and signal release time.

The headway between successive trains through unequal block lengths when $V_i = V_j$ can be determined as follows:

$$HW = \frac{BL_{max}}{V_i} + \frac{l}{V_i} + T_{FB} \tag{6}$$

The headway between successive trains through unequal block lengths when $V_i > V_j$ is determined from the first block length. When $V_i < V_j$, the headway is determined from all blocks.

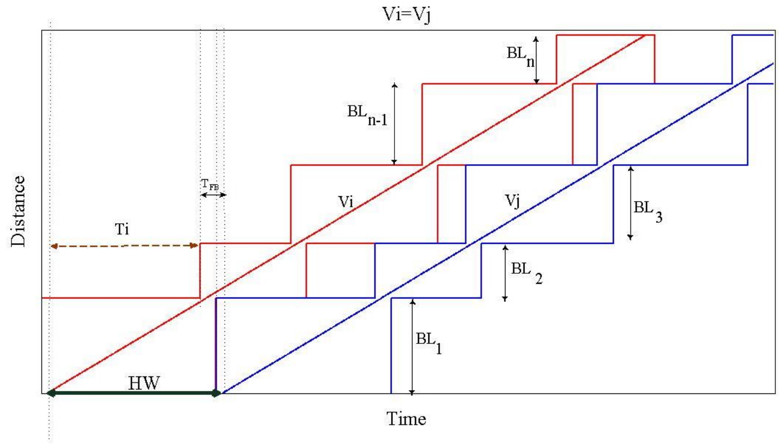

Fig. 7. Time–distance diagram for unequal block lengths when $V_i = V_j$ (Case 2-1).

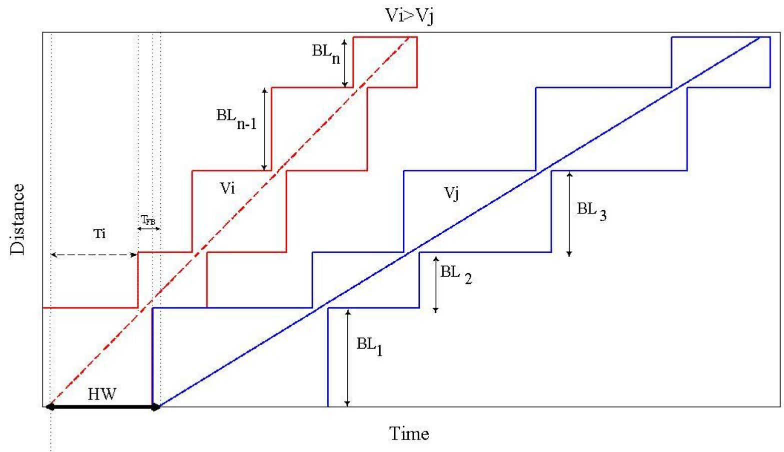

Fig. 8. Time–distance diagram for unequal block lengths when $V_i > V_j$ (Case 2-2).

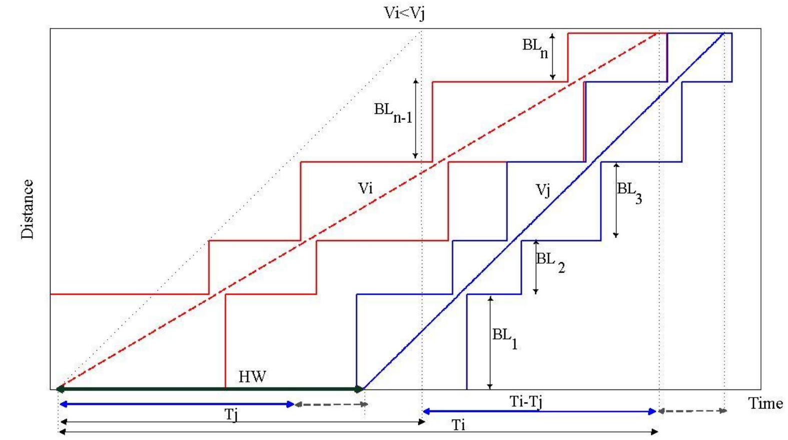

Fig. 9. Time–distance diagram for unequal block lengths when $V_i < V_j$ (Case 2-3).

Determination of the critical block under unequal block length operation was similar to that under equal block length operation:

- When $V_i > V_j$, the critical block length is the first block and
- When $V_i < V_j$, the critical block length is the last block.

Time headway in case Vi<Vj can be determined from the minimum headway between the two trains from the origin. The consideration involves the period from which train I leaving and completely clear critical block until just before train j is about to enter the block. Thus the minimum headway equals to the difference between time train i spent running from the origin to the critical block (Ti) and time train j spent running from the origin to the critical block (Tj) plus blocking time of train j in the critical block.

Figure 9 depicts the time-space diagram in which the critical block is the last block. In this case, the fourth of five total blocks was sufficiently long to warrant critical block designation. To prevent any conflict, all block lengths were considered hierarchically. The block lengths from each of the three cases of operation were checked sequentially. The maximum headway is the safe design headway and is determined as follows:

$$HW_n = \frac{l_i + \sum\limits_{\substack{i=1 \\ 1\le k\le n \\ k\in \mathrm{int}}}^{i=k} BL_i}{V_i} + \frac{\sum\limits_{\substack{i=1 \\ 1\le k\le n \\ k\in \mathrm{int}}}^{i=k-1} BL_i}{V_j} + T_{FB} + DT \tag{7}$$

Figure 10 depicts the stepwise process for determining a safe headway based on speed and distance along the rail line.

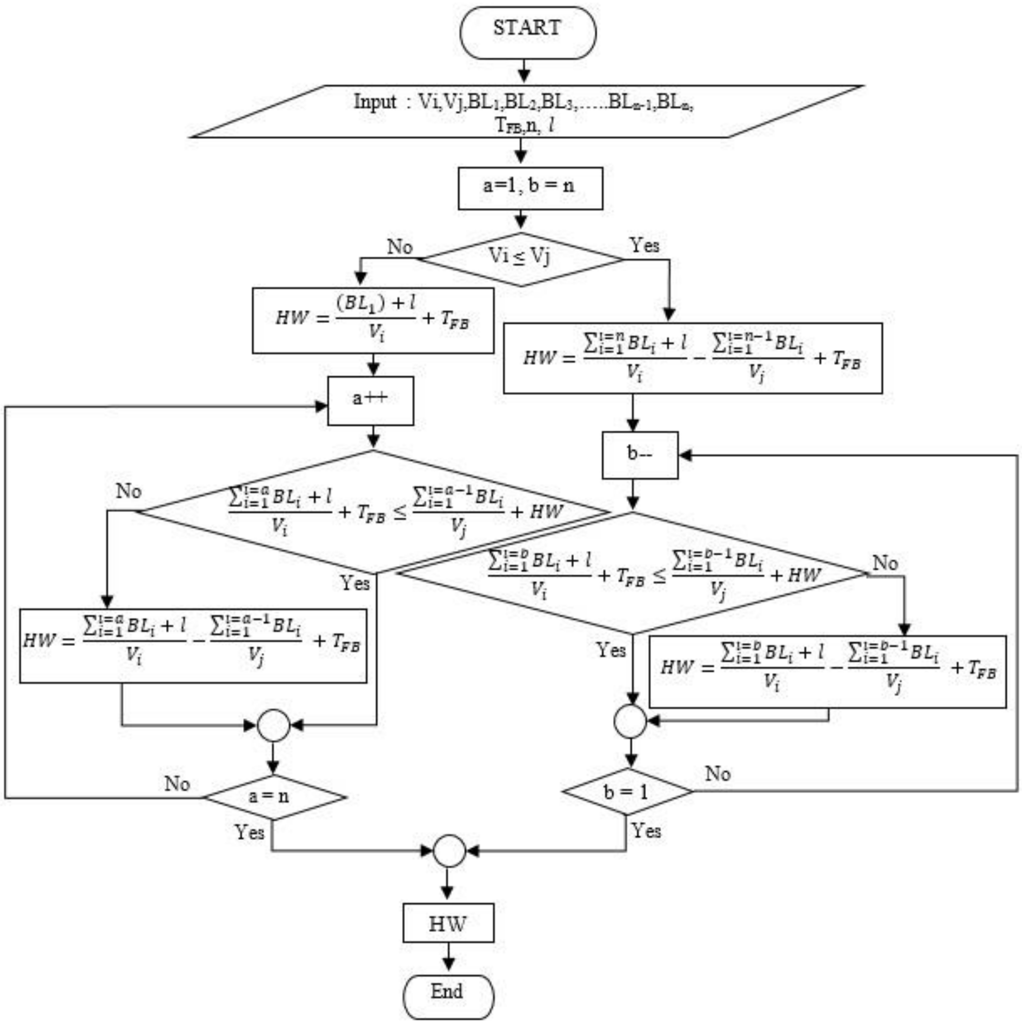

Fig. 10. Stepwise process for determining safe headways.

Using this stepwise process, headway determination begins with a review of both train speeds. If the leading train is faster, the analysis starts from the first block length and moves to each subsequent block. If the leading train is slower, the process is reversed, starting from the last block and moving to each prior block. This process can be applied to both equal and unequal block length situations.

The capacity when two types of trains operate alternately in a given time period (*T*) considers only the trains that completely cross a reference line. Under these operating conditions, capacity can be determined as follows [21]:

$$C = \frac{T - \frac{\sum_{i=1}^{i=n} BL_i}{V_i}}{HW_i + HW_j} + \frac{T - \frac{\sum_{i=1}^{i=n} BL_i}{V_j} - HW_i}{HW_i + HW_j} \tag{8}$$

where HW_i is the headway between the first and second trains, and HW_j is the headway between the second and third trains (with the same characteristics as the first).

For example, Figure 11 shows five pairs of trains with $V_i < V_j$ completely passing through a five-block section in one hour.

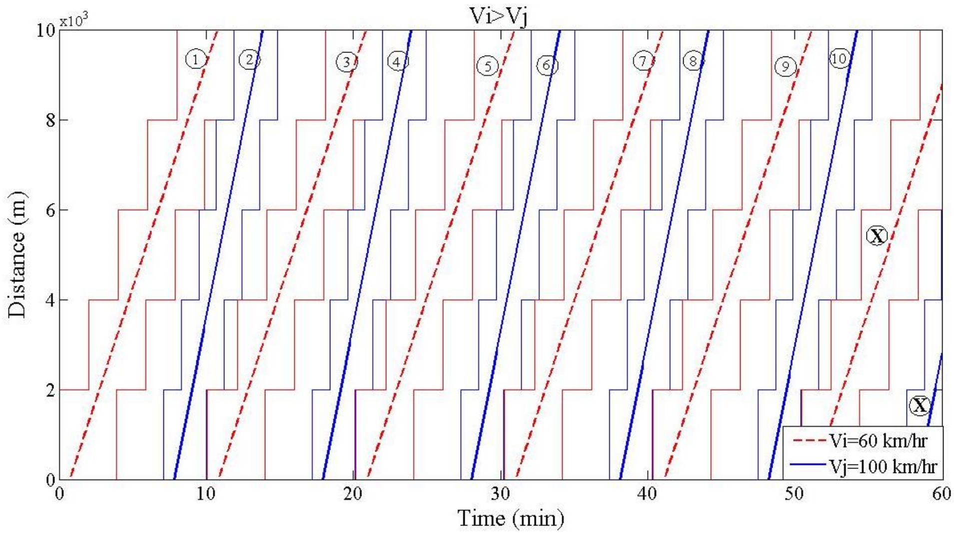

Fig. 11. Number of trains completely passing through a section in a specified period.

4. Results and Discussion

This study considered a five-block rail line section under equal and unequal (using the Northeastern Line layout) block length scenarios with train speeds of V_i and V_j. The findings regarding the effects of headway, speed, and block length on line capacity are described below.

4.1. Headway and Capacity

The maximum capacity occurred when two trains operated at the same speed. Higher speeds further reduced headway and increased capacity.

Figure 12 shows time–distance diagram indicating headway under various operational scenarios. When two trains operated at different speeds, the minimum headway changed depending on whether the faster train led or trailed the other train. Figure 12 (c–d) indicates that different headways should be assigned to achieve higher train flow. The stepwise process outlined previously in Fig. 10 can be used to find the most appropriate values for all cases.

When two trains operated at the same speed, the maximum block length determined the minimum headway consistent with Scott's formula. However, when train speeds were different, the maximum block length did not always determine the critical headway. Equation (7) can be applied to short sections under five blocks; longer sections can be analyzed using the stepwise process outlined previously in Fig. 10.

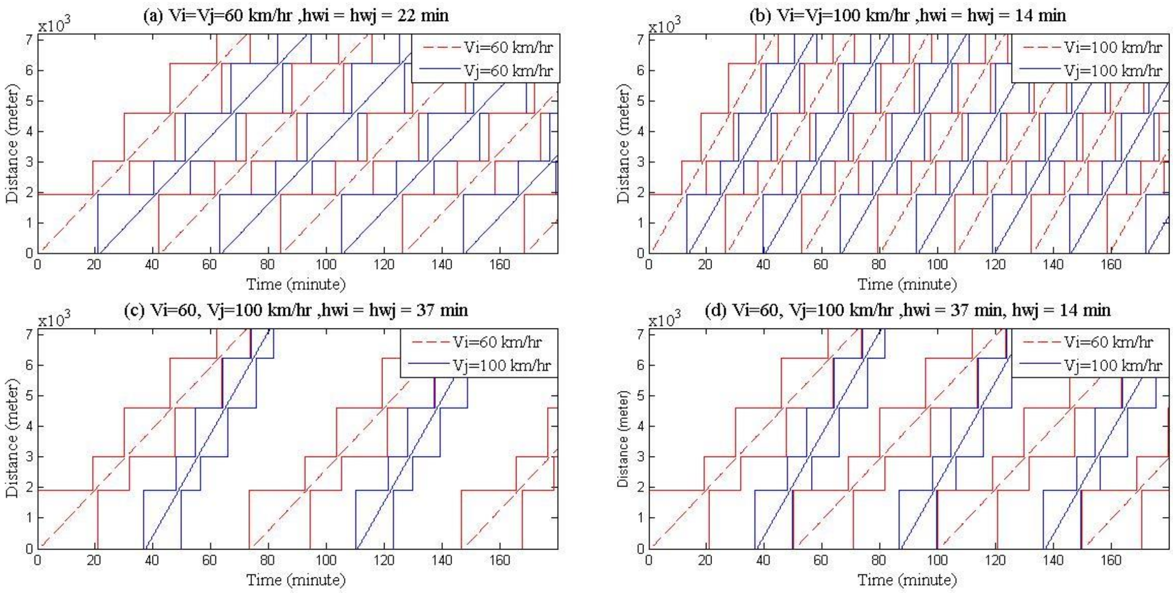

Fig. 12. Time–space diagrams showing headways under various operational scenarios.

4.2. Speed and Capacity

The speed difference (ΔV) was found to influence both headway and capacity. The highest capacity occurred when $V_i = V_j$. As the speed difference increased, the capacity decreased. Under the equal speed scenario, higher speeds yielded higher capacities. Figure 13 shows the relationship between speed difference and maximum number of trains each day for a 1 km block length. For reduced block lengths, the capacity is comparable to operations under equal speed with longer block lengths.

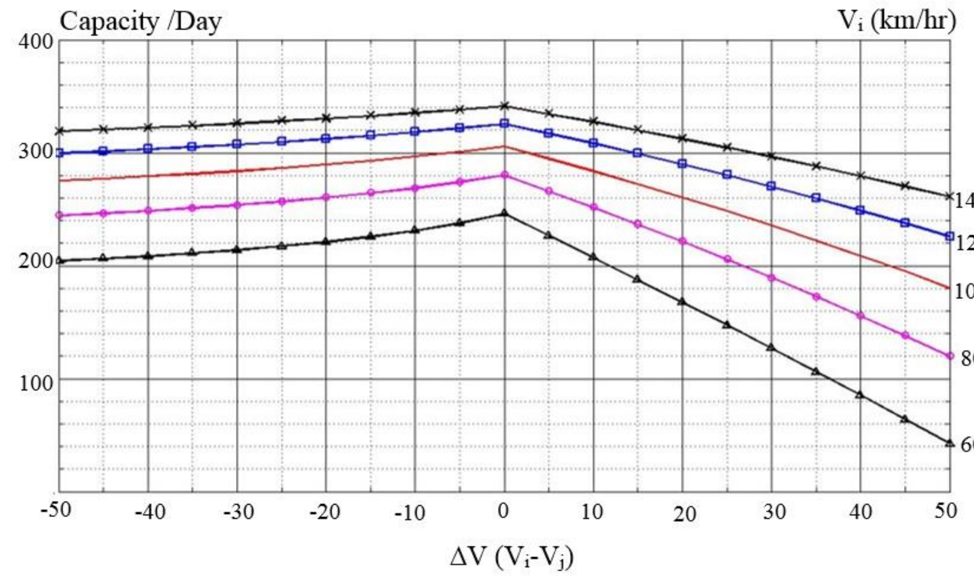

Fig. 13. Relationship between speed difference and line capacity.

4.3. Block Length and Capacity

Figure 14 shows that block length directly affected headway. For a block length of 8 km, the minimum headway was 10 min, resulting in a capacity of 34 trains per 6 h. When the block length was reduced to 2 km, the capacity increased to 84 trains per 6 h. The block length was limited by the speed-dependent braking distance [4, 22]. The suggested minimum block length is 1.5 times the braking distance [23]. For example, for a freight train operating at 50 km/h on a zero gradient with a required braking distance of 400 m, the minimum recommended block length is 600 m. Block length determination would therefore need to consider train speeds to accommodate and manage safe and efficient operation.

Figure 15 shows the relationship between number of blocks and capacity. When block lengths were equal, an increased number of blocks (*n*) resulted in an increased capacity.

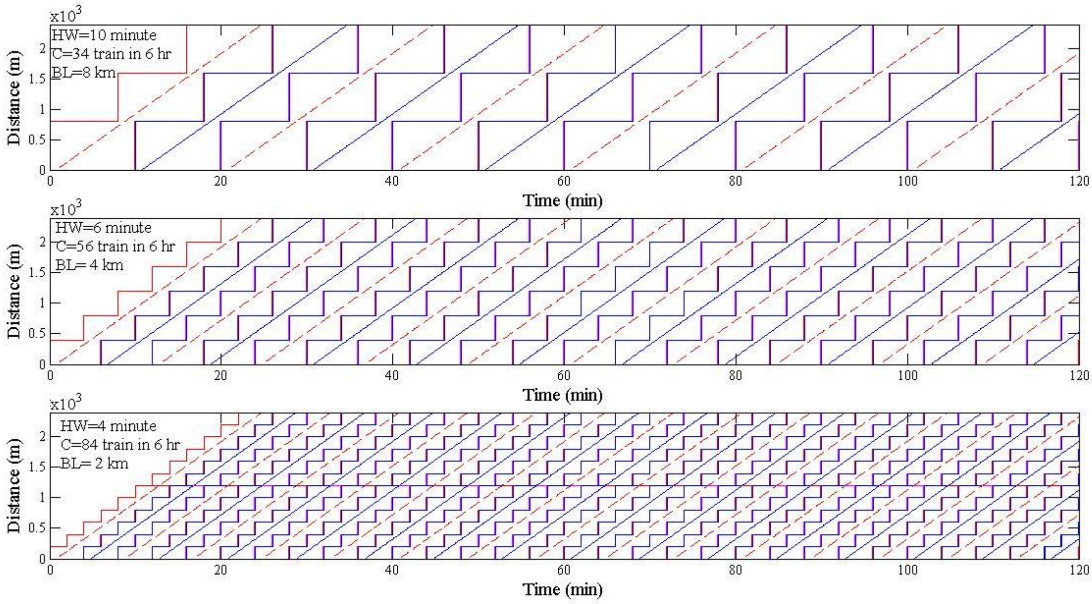

Fig. 14. Time–distance diagram for different block length scenarios.

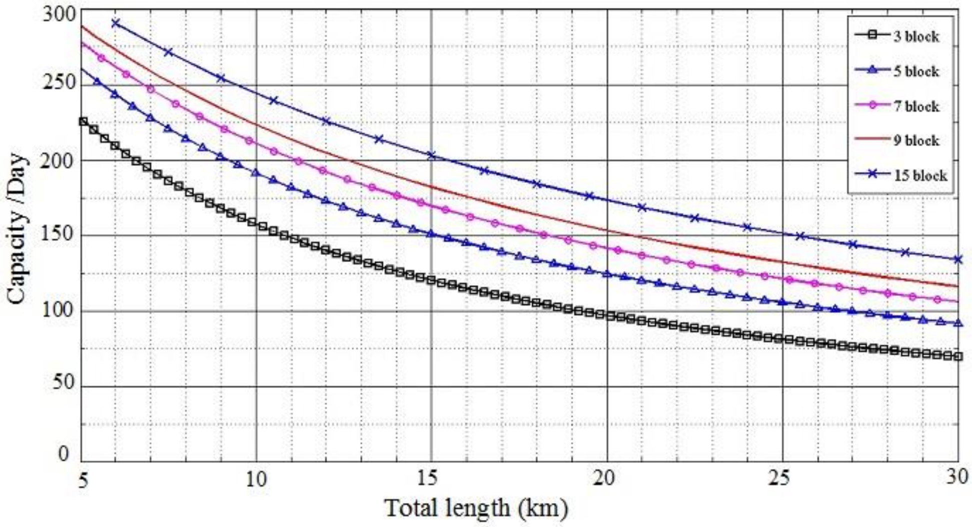

Fig. 15. Relationship between number of blocks and line capacity.

5. Conclusions

This study found that when trains with the same characteristics operated on unequal block length sections, the longest block was the critical block, which defined the minimum headway. For two trains with different speeds where the leading train was faster, the first block was initially assumed as the critical block. The minimum headway for the next block was subsequently calculated and checked for conflict. This stepwise analysis continued through the last block of the section. If the leading train was slower than the trailing train, the last block was assumed as the critical block and the stepwise analysis was repeated in reverse until no conflict existed.

The minimum headway was directly affected by the speed difference between two trains. As the speed difference increased, the headway also increased [24]. Other variables previously found to affect headways included train length [25]; block length [5]; the ratio of the summation of train length, block length, and stopping distance to speed [6]; and the ratio of train length to speed [26]. As block length decreases, capacity increases [27]. Therefore, capacity increases could be realized through double tracking and infrastructure improvements as well as through careful operational planning and management.

This article shall be useful for conceptual time headway determination for rail transit operators to plan short line operations or local operations at same specific sections. However, detailed train scheduling requires an analysis of travel time from station to station, including a train's acceleration, cruising, coasting, and deceleration. In addition, it requires careful consideration of passing locations, which can be achieved through optimization models to determine the most efficient minimum headway.

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References

[1] Office of Transport and Traffic Policy and Planning, "The Study of Railway Development Master Plan," Executive Summary Report, 2010.
[2] F. Li, J.-B. Sheu, and Z.-Y. Gao, "Deadlock analysis, prevention and train optimal travel mechanism in single-track railway system," *Transportation Research Part B: Methodological*, vol. 68, pp. 385-414, 2014.
[3] E. R. Gafarov, A. Dolgui, and A. A. Lazarev, "Two-station single-track railway scheduling problem with trains of equal speed," *Computers & Industrial Engineering*, vol. 85, no. 260-267, 2015.
[4] T. Parkinson, "Rail transit capacity," Transportation Research Board, National Research Council Washington, D.C., TCRP Report 13, 1996.
[5] C.-K. LEE, "The minimum headway of a rail transit line," *Joumal of the Eastem Asia Society for Transportation Studies*, vol. 2, no. 1, 1997.
[6] A. Landex and A. H. Kaas, "Planning the most suitable travel speed for high frequency railway lines," in *1st International Seminar on Railway Operations Modelling and Analysis*, TU Delft, Delft, 2005.
[7] T. Lindner, "Applicability of the analytical UIC Code 406 compression method for evaluating line and station capacity," *Journal of Rail Transport Planning & Management*, vol. 1, no. 49-57, 2011.
[8] J. C. Fransoo and J. W. M. Bertrand, "An aggregate capacity estimation model for the evaluation of railroad passing constructions," *Transportation Research Part A: Policy and Practice*, vol. 34, pp. 35-49, 2000.
[9] T. Huisman and R. J. Boucherie, "Running times on railway sections with heterogeneous train traffic," *Transportation Research Part B: Methodological*, vol. 35, pp. 271-292, 2001.
[10] S. Harrod, "Capacity factors of a mixed speed railway network," *Transportation Research Part E: Logistics and Transportation Review*, vol. 45, pp. 830-841, 2009.
[11] G. Medeossi, G. Longo, and S. de Fabris, "A method for using stochastic blocking times to improve timetable planning," *Journal of Rail Transport Planning & Management*, vol. 1, pp. 1-13, 2011.
[12] T. Fumasoli, D. Bruckmann, and U. Weidmann, "Operation of freight railways in densely used mixed traffic networks—An impact model to quantify changes in freight train characteristics," *Research in Transportation Economics*, vol. 54, no. 15-19, 2015.
[13] S. de Fabris, G. Longo, G. Medeossi, and R. Pesenti, "Automatic generation of railway timetables based on a mesoscopic infrastructure model," *Journal of Rail Transport Planning & Management*, vol. 4, no. 2-13, 2014.
[14] A. A. Assad, "Models for rail transportation," *Transportation Research Part A: General*, vol. 14, pp. 205-220, 1980.
[15] T. Büker, "Methods of assessing railway infrastructure capacity," *Engineering Science and Technology, an International Journal (JESTECH)*, vol. 16, pp. 39-51, 2013.
[16] UIC, "UIC CODE 406R-capacity-1st edition," in *UIC CODE 406*R. France: International Union of Railways, 2004.

[17] I. A. Hansen and J. Pachl, *Railway Timetabling & Operations: Analysis, Modelling, Optimisation, Simulation, and Performance Evaluation*, 2nd ed. Hamburg: Eurailpass, 2014.

[18] J. Pachl, *Railway Operation and Control*. Mountlake Terrace, USA: VTD Rail Publishing, 2002.

[19] M. Heydar, M. E. H. Petering, and D. R. Bergmann, "Mixed integer programming for minimizing the period of a cyclic railway timetable for a single track with two train types," *Computers & Industrial Engineering*, vol. 66, no. 171-185, 2013.

[20] R. M. P. Goverde, F. Corman, and A. D'Ariano, "Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions," *Journal of Rail Transport Planning & Management*, vol. 3, pp. 78-94, 2013.

[21] M. Abril, F. Barber, L. Ingolotti, M. A. Salido, P. Tormos, and A. Lova, "An assessment of railway capacity," *Transportation Research Part E: Logistics and Transportation Review*, vol. 44, pp. 774-806, 2008.

[22] H. Liu, B. Mao, B. Wang, P. Du, and Y. Ding, "Optimization of railway section signalling layout based on quasi-moving block," *Journal of Transportation Systems Engineering and Information Technology*, vol. 11, pp. 103-109, 2011.

[23] V. A. Profillidis, *Railway Management and Engineering*, 3rd ed. Aldershot, England; Burlington, VT, USA: Ashgate, 2006.

[24] S. Mitra, D. Tolliver, and S. Mitra, "Estimation of railroad capacity using parametric methods," *Journal of the Transportation Research Forum*, vol. 49, no. 111-126, 2010.

[25] J. H. Banks, *Introduction to Transportation Engineering*, 2nd ed. New York: McGraw-Hill, 2012, pp. 251-282.

[26] B. Mao, J. Liu, Y. Ding, H. Liu, and T. K. Ho, "Signalling layout for fixed-block railway lines with real-coded genetic algorithms," *Hong Kong Institution of Engineers, Transactions*, vol. 13, no. 1, 2006.

[27] A. Dicembre and S. Ricci, "Railway traffic on high density urban corridors: Capacity, signalling and timetable," *Journal of Rail Transport Planning & Management*, vol. 1, pp. 59-68, 2011.