AN ESTIMATION OF CAPACITY

ON RAILWAY NETWORK

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A Thesis Submitted in Partial Fulfilment of the Requirements for the

Degree of Doctor of Philosophy in Transportation Engineering

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การประมาณความจุบนโครงข่ายทางรถไฟ

นางสาวอรอนงค์ แสงผ่อง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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ปัจจุบัน ประเทศไทยประเมินค่าความจุสายทางจากการใช้สมการสกอตต์ ซึ่งให้ค่าความจุที่ต่ำกว่าความจุที่แท้จริง ดังนั้น การศึกษานี้จึงได้เล็งเห็นความสำคัญในการวิเคราะห์ความจุให้สอดคล้องกับลักษณะการเดินรถในประเทศไทย ซึ่งยังคงเป็นการเดินรถในเส้นทางลักษณะตอนเดินรถไม่เท่ากัน และเพื่อเป็นแนวทางสำหรับการศึกษาการเพิ่มความจุให้กับสายทาง โดยมีวัตถุประสงค์ ดังนี้ 1) เพื่อวิเคราะห์ตอนเดินรถวิกฤตที่เป็นตัวกำหนดระยะเวลาระหว่างขบวนรถไฟน้อยที่สุดของเส้นทาง และปัจจัยที่มีผลต่อความจุสายทาง 2) เพื่อออกแบบเครื่องมือที่สามารถใช้ทดแทนการวิเคราะห์ด้วยสมการทางคณิตศาสตร์สำหรับหาระยะเวลาระหว่างขบวนรถไฟได้ 3) เพื่อศึกษาการวิเคราะห์ระยะเวลาระหว่างขบวนรถไฟ เวลาจอด และความสัมพันธ์ระหว่างความจุกับตำแหน่งที่แซงในเส้นทางตอนเดินรถเท่ากัน และ 4) เพื่อวิเคราะห์ตำแหน่งแซงที่เหมาะสมในเส้นทางตอนเดินรถไม่เท่ากัน โดยใช้ขั้นตอนวิธีเชิงพันธุกรรม และประมาณค่าความจุที่เพิ่มขึ้น โดยแบ่งการศึกษาออกเป็น 4 ส่วน

จากการศึกษาส่วนแรก พบว่า การกำหนดระยะห่างระหว่างขบวนรถไฟต่ำสุดเป็นฟังก์ชั่นของความเร็วและความยาวขบวนรถ ความยาวของตอนเดินรถและจำนวนตอนเดินรถ ในกรณีที่ความเร็วขบวนแรกและขบวนที่ตามมามีความเร็วเท่ากันบนสายทางที่ความยาวของตอนไม่เท่ากัน ช่วงระยะเวลาในตอนที่ยาวที่สุดจะเป็นตัวกำหนดค่าระยะห่างระหว่างขบวน ขณะที่กรณีรถไฟมีความเร็วแตกต่างกันจะไม่มีสูตรสำเร็จในการคำนวณ ซึ่งตอนเดินรถที่มีความยาวมากที่สุดไม่ใช่ตอนเดินรถวิกฤตเสมอไป แต่ต้องพิจารณาเป็นลำดับขั้นเพื่อหาระยะห่างระหว่างขบวนที่สั้นที่สุด โดยที่ความแตกต่างของความเร็วยิ่งมาก ความจุยิ่งน้อย การลดตอนเดินรถ สามารถช่วยเพิ่มความจุได้

สำหรับการศึกษาส่วนที่ 2 ซึ่งเป็นการศึกษาการสร้างเครื่องมือเพื่อช่วยให้สามารถหาคำตอบของระยะห่างระหว่างขบวนรถไฟอย่างง่าย โดยการใช้โนโมกราฟ ทดแทนการวิเคราะห์จากสมการ โนโมกราฟที่สร้างขึ้นสามารถนำไปวิเคราะห์หาระยะห่างระหว่างขบวนรถไฟได้อย่างมีประสิทธิภาพ ถึงแม้ว่าการวิ่งด้วยระยะเวลาระหว่างขบวนรถไฟน้อยที่สุด จะทำให้ความจุสูงสุดแล้ว แต่ในกรณีที่รถไฟช้าวิ่งนำรถไฟเร็วเป็นตัวทำให้ความจุต่ำ เนื่องจากจำเป็นต้องมีระยะห่างมากเพียงพอเพื่อความปลอดภัยในการวิ่งตามกัน ดังนั้นการลดระยะเวลาระหว่างขบวนรถไฟน้อยที่สุดเพื่อจัดการให้รถไฟเร็วแซงรถไฟช้า สามารถเพิ่มความจุให้กับสายทางได้ โดยความจุที่เพิ่มขึ้น

ขึ้นอยู่กับตำแหน่งที่แซง จากการศึกษาในส่วนที่ 3 การวิเคราะห์ตำแหน่งแซงที่เหมาะสมในเส้นทางที่ความยาวตอนเดินรถเท่ากัน ตำแหน่งแซงที่เหมาะสมจะอยู่บริเวณตอนเดินรถกึ่งกลางของสายทาง ซึ่งหาได้จากจำนวนตอนเดินรถในสายทางได้โดยตรง กราฟแสดงความสัมพันธ์ระหว่างตำแหน่งที่แซงกับความจุสายทางมีลักษณะเชิงสมมาตร โดยตำแหน่งแซงบริเวณตรงกลางจะให้ค่าความจุมากที่สุด และความจุจะลดลงเรื่อย ๆ เมื่อตำแหน่งแซงออกห่างจากโซนกลาง

สำหรับการศึกษาส่วนสุดท้าย เป็นการศึกษาหาตำแหน่งแซงที่เหมาะสมในเส้นทางความยาวตอนเดินรถไม่เท่ากัน โดยใช้ขั้นตอนวิธีเชิงพันธุกรรมจากโปรแกรมแมตแล็บ สำหรับการวิเคราะห์หาคำตอบจากการวิเคราะห์เส้นทางที่กำลังก่อสร้างจากทางเดี่ยวเป็นทางคู่ในเส้นทางจากสถานีชุมทางจิระ-ขอนแก่น ภายใต้ข้อจำกัดด้านระยะห่างระหว่างขบวนปลอดภัย ระยะเวลาจอด และการใช้ตอนเดินรถ พบว่า สถานีศาลาดิน เป็นตำแหน่งแซงที่เหมาะสม ช่วยเพิ่มความจุของสายทางเมื่อเปรียบเทียบกับการจัดการเดินรถแบบไม่แซงกัน ได้ถึงร้อยละเฉลี่ย 76

สาขาวิชา วิศวกรรมขนส่ง ลายมือชื่อนักศึกษา ________________________

ปีการศึกษา 2559 ลายมือชื่ออาจารย์ที่ปรึกษา ____________________

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ________________

ONANONG SANGPHONG : AN ESTIMATION OF CAPACITY ON RAILWAY NETWORK. THESIS ADVISOR : ASSOC. PROF. VATANAVONGS RATANAVARAHA, Ph.D., 122 PP.

MINIMUM HEADWAY/NOMOGRAPHS/CRITICAL BLOCK/
TRAIN SCHEDULE/CAPACITY/OVERTAKE/BLOCKING TIME

Presently, State Railway of Thailand (SRT) evaluates the capacity of the line from Scott's equation, which normally yields lower results than the actual capacity. This study recognizes the importance to analyze true line capacity in consistent with the real operations in Thailand. The study would provide approaches to increase line capacity. The objectives of this research were (1) to analyze a critical block determining minimum time headway and factors influencing line capacity, (2) to design the tool replacing mathematical analysis for time headway, (3) to study the effects of the overtaking point to line capacity on equal block length, and (4) to analyze the suitable overtaking point of unequal block length operation by using the genetic algorithm and estimate the increasing capacity.

The study was divided into four sections, according to the objectives. The first part of the study illustrated that the capacity, in form of minimum safe headway was a function of the train speed, train length, block length, and number of blocks. 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. The maximum capacity was achieved when two trains operated at the same speed. As block length decreases, capacity increases.

The second study proposes the design and analysis of nomographs for minimum headway calculations to reduce the complexity of mathematical equations. The validation reveals that the nomographs yield minimum headways that are close to the result obtained by mathematical derivation. Although minimum time headway make highest capacity, allowing slower train leads faster one decreases capacity as a large safe following distance must be provided. Scheduling passing for trains with different speeds will improve the line capacity. The study in the third section addresses optimal overtaking position under an equal block length section. The overtaking block position depends on the number of blocks. The graph between the overtaking position and capacity is symmetrical, in which capacity is maximized when the overtaking position is exactly in the middle, and is reducing when the overtaking position is far from the center of the line.

The last section of the study was the analysis of the appropriate overtaking position on unequal block length section using genetic algorithms in MATLAB program. The study presents a case study on Thanon Chira Junction to Khon kaen section which are currently under double track project construction. The analysis is performed under the limitation of headway, dwell time constraints and fixed block condition to protect conflict throughout the route. It was found that Sa La Din station is the most appropriate overtaking station which increased the route capacity 76 percent compared with train following arrangement.

School of Transportation Engineering　　　Student's Signature_________________

Academic Year 2016　　　Advisor's Signature_________________

Co-Advisor's Signature______________

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SYMBOLS AND ABBREVIATIONS

BL	=	Block length (m)
l	=	Train length (m)
V_i	=	Speed of train i
V_j	=	Speed of train j
ct	=	Clearing time in the block (s)
rt	=	Release time (s)
wt	=	Signal watching time (s)
tfc	=	Signal clearing time (s)
ΔV	=	Speed difference
n	=	number of blocks
D_{bmax}	=	Distance from the origin station to the end of the longest block
D_n	=	Distance from origin to destination
BL_{max}	=	Maximum block length
HW_{ij}	=	Headway between trains i and j
HW_{ji}	=	Headway between trains j and i
m	=	overtaking block
T_{FB}	=	Time for block
DW	=	Dwell time
C	=	Line capacity

CHAPTER I

INTRODUCTION

1.1 RATIONALE FOR THE RESEARCH

At present, many countries are facing the problem of too many personal cars within the countries. This causes the countries' shortcomings regarding pollution emission overwhelming surroundings, high energy demand, and traffic congestion. The governments in these countries try to solve the mentioned problems by enhancing the reduction of personal cars such as the announcement of car free day, the limitation of traffic zones, the control of private car growth, the campaign for people's public transport promotion, and the stimulation and encouragement of sustainable transport system. Liu et al. have presented the strategy of sustainable transport system in China with the system of high speed railway (HSR), urban rail transit (URT) and electric vehicle (EV) to reduce CO_2 emission and save energy (Liu, Lund, & Mathiesen, 2013). India has promoted the transport by rail system instead of roads and aeroplanes (Gangwar and Sharma 2014).The UK Government sets a target to reduce CO_2, which is largely emitted by transport sector, by 60% within 2050 (Engineering, 2005)and provides substitute energy alternatives (Raslavičius, Keršys et al. 2014). Thai government has given the importance to fundamental infrastructure development of rail transportation by changing single-track railways to double-track railways in order to increase the efficiency of rail system reducing time of travel, providing punctuality, saving fuel energy used in transportation sector of country, and reducing the pollution problem to surroundings.

Rail system is an eco-friendly transport system classified as transportation type emitting a little greenhouse gas as shown in Figure 1.1, having efficiency of transporting people and goods per a unit of energy, serving a large number of people in each time, and being the safest transport system. Thus, many countries have opinion to change the travel transport to be rail system widely. Thailand firstly began developing rail transport in the reign of King Rama V since he recognized the importance of transportation which would form the nationally developmental basis of transportation in Asian region. However, since those days, the capability of rail system was not so much developed as our neighbor. In 2015, Thailand had to make preparation for entering ASEAN community; therefore Ministry of transport had policy for accelerating the development of the rail system into the infrastructure solution. The government agreed at the project to develop the rail system in northern, northeastern, and southern part of Thailand total 873 km. However, the study to plan the prototype of 2010 cannot clearly indicate the capability level of the routes serving increasing trains. (Office of Transport and Traffic Policy and Planning 2010)

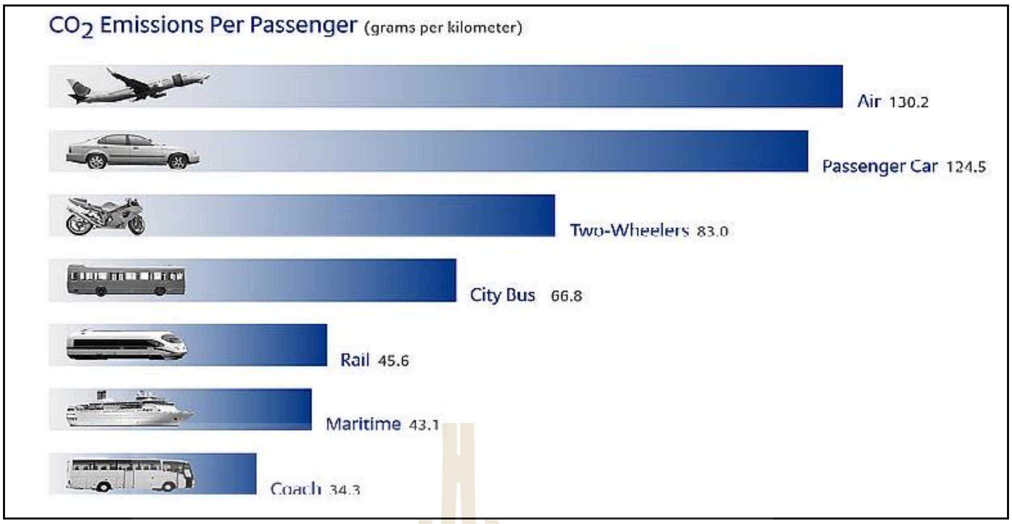

Figure 1.1 : Greenhouse Gas Emission according to types of Travel Transports (Knowledge, 2010)

The capacity of rail system is the indicator reflecting the ability of train service given. At present, state railway of Thailand uses Scott 's formula (Office of Transport and Traffic Policy and Planning 2010) for finding the capacity of each route throughout the country by considering the speed at 55 km/ per hour which is the slowest speed of warehouse train. However, the capacity of the rail system depends on the train timetable and can be the problem because of variables under complicated conditions for decision making. For example, the arrangement of timetable of a lot of trains simultaneously and most effectively using the train resources to minimize the delay of trains, and the reduction of travel time between passenger stations will increase the capacity (Siradol Sirithorn, 2010). Moreover, the development of single rail way into double rail way will help increase the capacity.

The number of trains on routes can be estimated by average returning time between two trains. Therefore, for getting increasing capacity, we must minimize time headway. The calculation of minimum headway time depends on kinds of trains. (Büker, 2013), block length (LEE, 1997; Parkinson, 1996), the train length(Emery, 2009), the speed (Emery, 2009), average acceleration breaking speed rates (Parkinson, 1996), blocking time when the train is allowed to enter the block until the train leaves the block (de Fabris, Longo, Medeossi, & Pesenti, 2014; Fumasoli, Bruckmann, & Weidmann, 2015; Medeossi, Longo, & de Fabris, 2011)

This research studied the train running management from the determination of minimum time headway under a variety of conditions such as the different speed of each train, block length on the basis of blocking time model by using time space diagram and investigated the increase of route capacity by managing the fast trains able to overtake the slow train for solving the conflict areas. The study was divided into the management on rotes with equal block length and unequal block length. For unequal block length, critical block is complicated to check. Therefore, the examination of headway time in case that the train ran after another train, flowchart had to be used for checking in each step to protect conflict occurrence. In case that the train overtook another train, genetic algorithm was used to analyze the point of overtaking which increased the maximum route capacity.

1.2 PURPOSES OF THE RESEARCH

1.2.1 To analyze critical block determining minimum time headway on route and factors influencing route capacity.

1.2.2 To design the tool replacing mathematic equation analysis for time headway

1.2.3 To study the analysis of time headway, dwell time and the relation between the capacity and the overtaking point on equal block length

1.2.4 To analyze the suitable overtaking point of unequal block length by using genetic algorithm and estimate the increasing capacity

1.3 SCOPE OF THE RESEARCH

1.3.1 The analysis of minimum headway under the same direction train running by managing the pattern of train following another one and that of the train overtaking another on the basis of blocking time model.

1.3.2 Types of routes were divided based on block length comprising equal and unequal block lengths.

1.3.3 The results from the geometrical basis time space diagram are compared with ones from algorithm.

1.3.4 For area of study, within the double railway project of Thanon Chira Junction -Khonkaen station

1.3.5 The study only considers intercity double-track operation.

1.3.6 The study assumes 2-aspect signaling system. The acceleration and deceleration only occurs after leaving and before arriving the stations respectively.

1.3.7 Types of trains include passenger, freight train. It is assumed, for sake of simplicity, that all trains and it does not stop at the station.do not stop at the stations.

The scope research is designed to answer all 4 study objectives as illustrated in Fig 1.2.

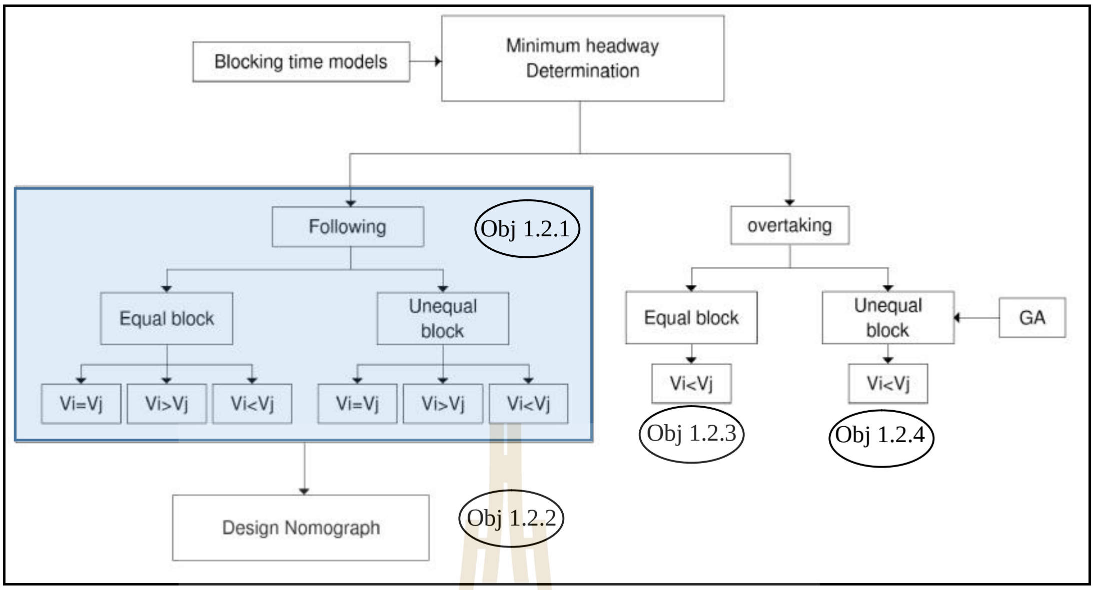

Figure 1.2: Overview of the study

1.4 RESEARCH QUESTIONS

1.4.1 For train running management in Thailand such as the pattern of time scheduling management. Light signal box, the speed of each kind of train which runs on the same route, the method to acquire the rail system capacity should be conducted to obtain more capacity than the identification of that from Scott's formula.

1.4.2 The essential variables which should be considered included train characteristic, infrastructure characteristic, and control system to schedule time train table providing maximum route capacity, and identify the factors determining minimum time headway.

1.4.3 Identify the appropriate position for the slow train overtaking the fast train and how the increasing capacity relates to the overtaking point.

1.5 CONTRIBUTION OF THE RESEARCH

1.5.1 This research can be taken to analyze other route capacity.

1.5.2 In case of single-track railway development demand or double-track future development, where to arrange the trains' positions for overtaking or stepping aside will be known to increase line capacity.

1.5.3 And the design of short distance travel arrangement or local routes.

1.5.4 Capacity estimation using simple method.

1.5.5 Determine critical stations for improvement.

1.5.6 Train scheduling to achieve high capacity.

1.6 ORGANIZATION OF THE RESEARCH

This thesis was conducted in journal thesis format comprising research articles divided by research objectives. This journal thesis is divided into 6 chapters as follows;

Chapter 1: Expressing the importance and rationale of research questions of this research. Scope of study, research objectives, research questions, and benefits expected from this study.

Chapter 2: Literature review on capacity, headway, blocking time and nomograph.

Chapter 3: Determining critical line blocks and minimum train headways for equal and unequal block lengths and various train speed scenarios: is to explain and analyze minimum time headways in the situation of having same and different speed, equal and unequal block length by using graph time space diagram to find out critical blocks.

Charter 4: Analysis and design of Nomographs for minimum headway calculation: Presenting the application of Nomograph for analyzing the minimum time headway by using PyNomo program that was written under the involved variables with headway including speed, block length, train length, by using Python script. The design of Nomograph was divided into three forms: the first train had equal speed as the second train (Vi=Vj), the first train had more speed than the second train (Vi>Vj), the first train had less speed than the second train (Vi<Vj)

Charter 5: Analysis of appropriate overtaking position under equal block lengths: Analyzing the overtaking position acquiring the most capacity in case of equal block length by analyzing the comparison between the steep of train running on the Time space diagram and analyze the factors determining appropriate position of each route.

Charter 6: Defining the optimal train overtaking position using genetic algorithm: focusing on the study of overtaking position using genetic algorithm, the analysis of the maximum increase of route capacity by having the objective function considered in this subject which was the maximum capacity railway at the optimal overtaking position under the limitation of safe headway, dwell time constraints and fixed block condition by using MATLAB program analyzing Thanon Chira Junction -Khonkaen station

Charter 7: Conclusion and recommendations: This section concludes the results from chapters 3-7 and gives the suggestions from the findings.

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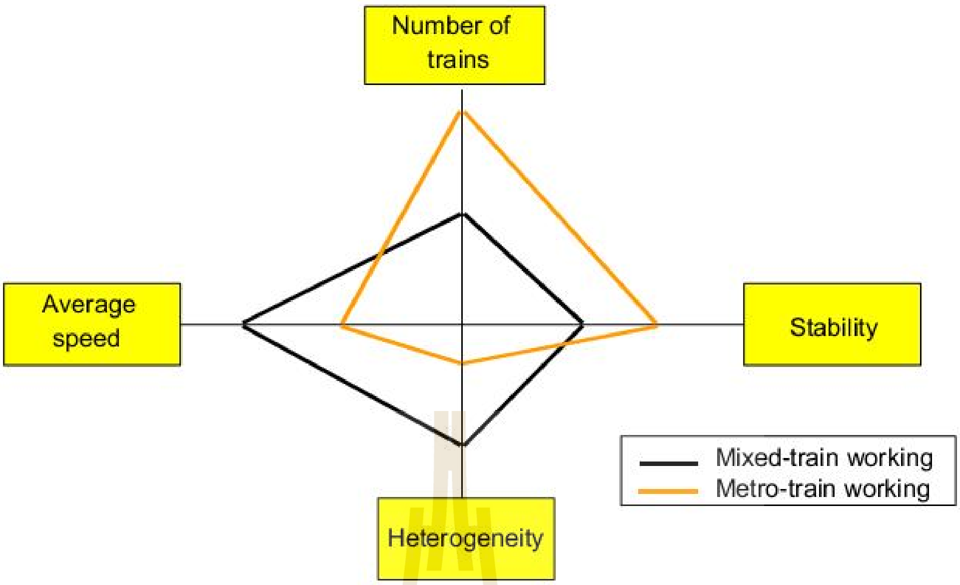

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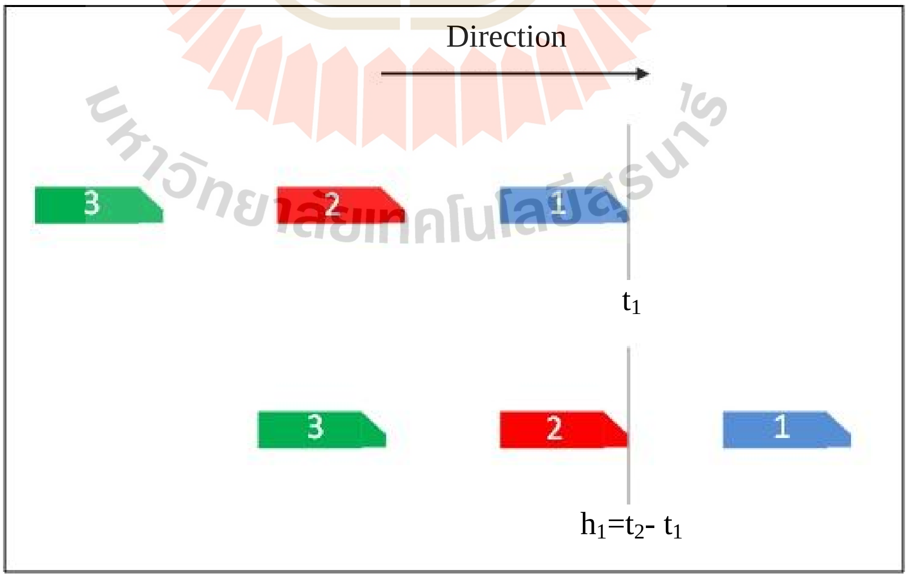

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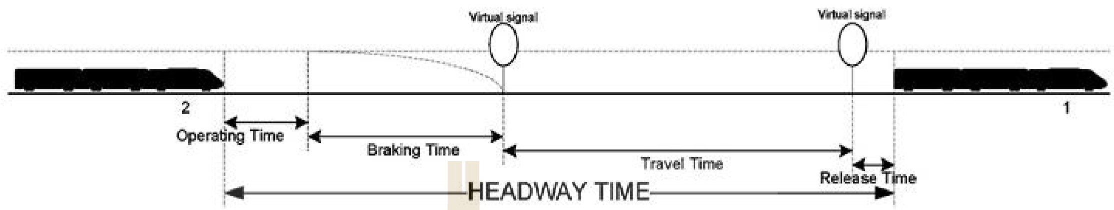

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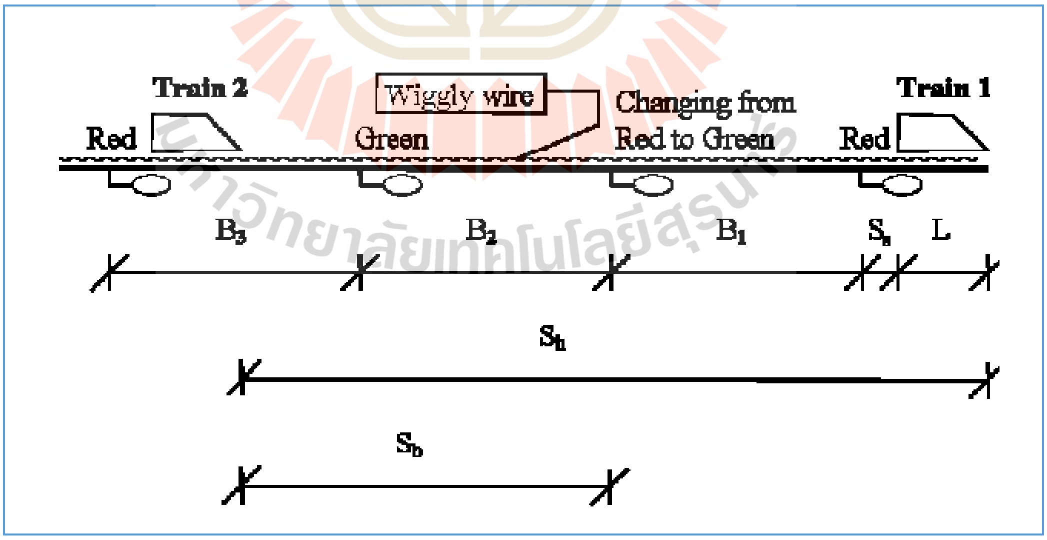

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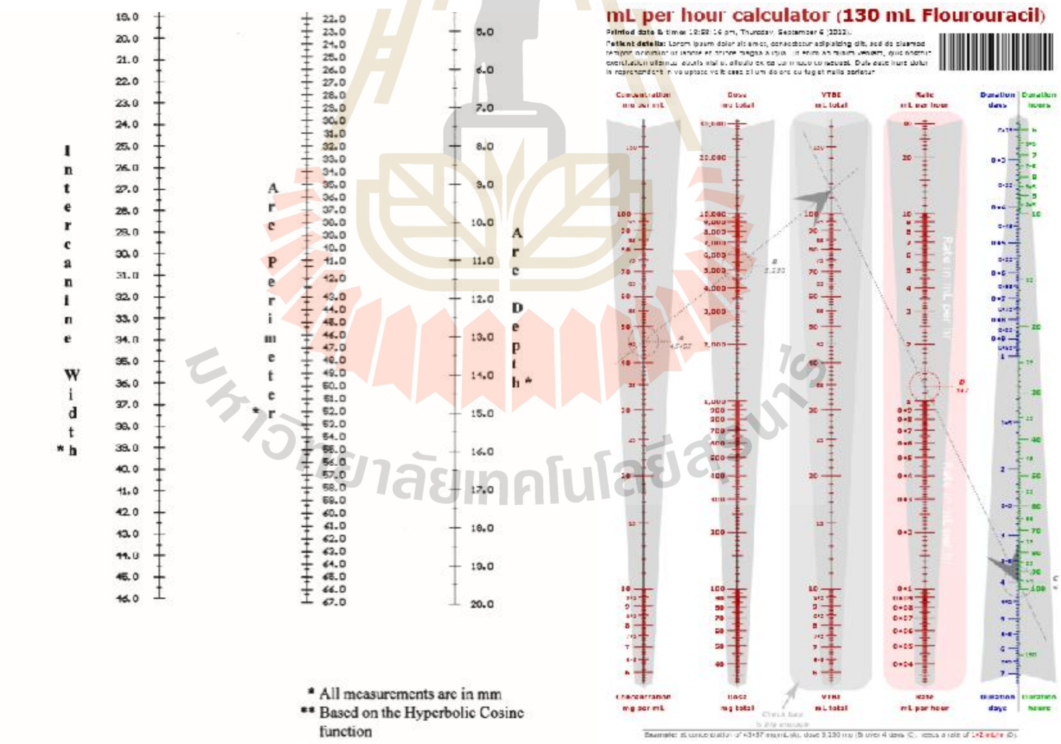

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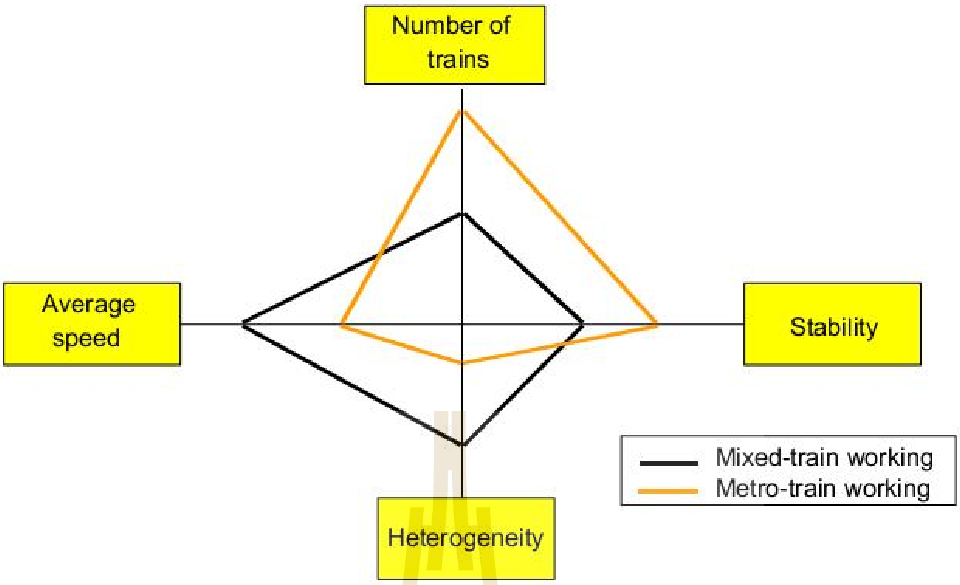

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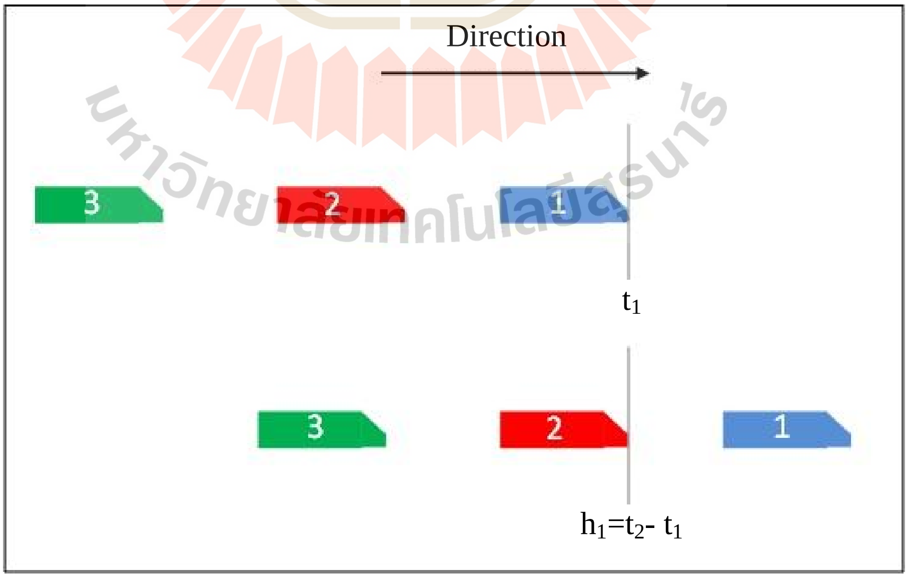

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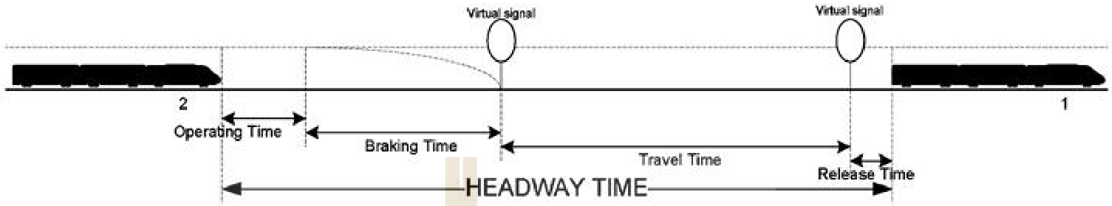

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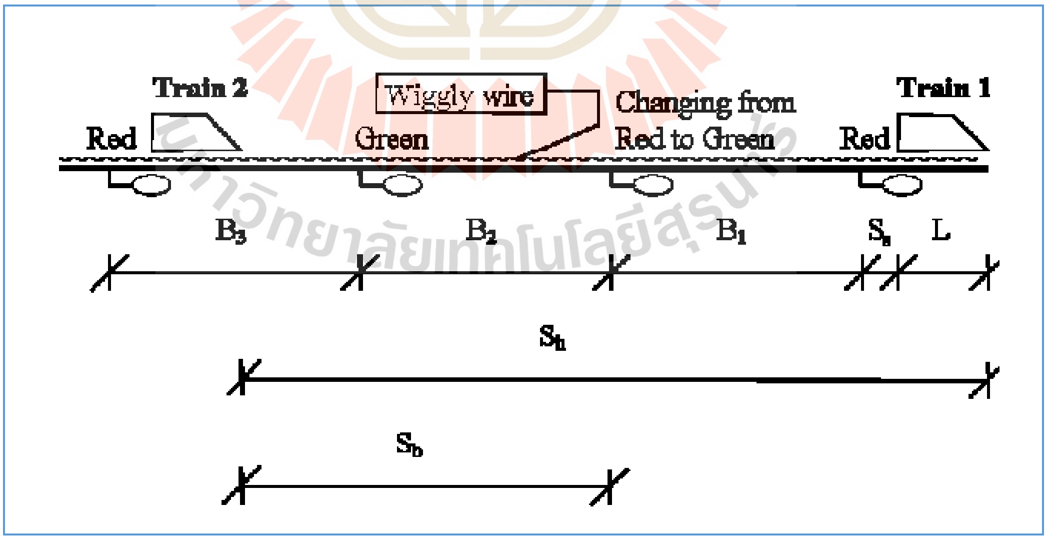

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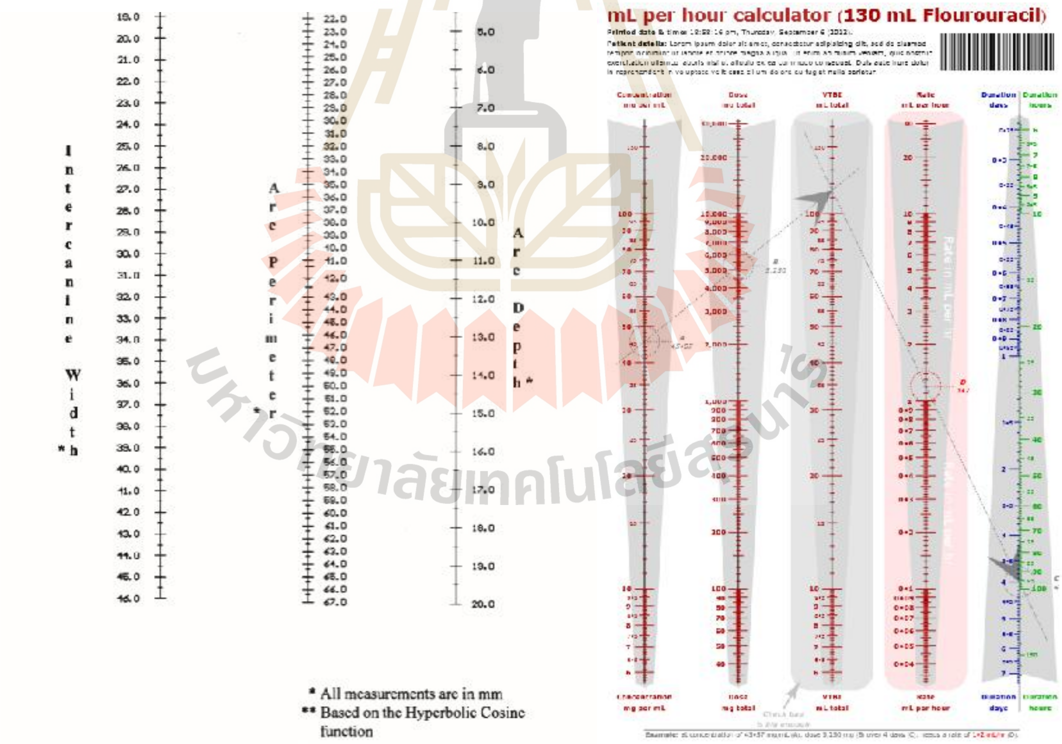

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CHAPTER III

DETERMINING CRITICAL RAIL LINE BLOCKS AND MINIMUM TRAIN HEADWAYS FOR EQUAL AND UNEQUAL BLOCK LENGTHS AND VARIOUS TRAIN SPEED SCENARIOS

3.1 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.

3.2 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 (Office of Transport and Traffic Policy and Planning 2010).

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 (Gafarov, Dolgui, & Lazarev, 2015; Li, Sheu, & Gao, 2014) determining the optimal running time, minimum headway, and capacity on a block length basis (Landex & Kaas, 2005; LEE, 1997; Parkinson, 1996) for trains operating with the same speed (Lindner, 2011) and different speeds (Fransoo & Bertrand, 2000; Harrod, 2009; Huisman &

Boucherie, 2001) and using blocking time models (de Fabris, Longo, Medeossi, & Pesenti, 2014; Fumasoli, Bruckmann, & Weidmann, 2015; Medeossi, Longo, & de Fabris, 2011). Studies on train scheduling and blocking time particularly benefited railway simulation (Assad, 1980). A focus on, and subsequent modifications to, blocking time addressed problems in many countries (Büker, 2013). 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.

3.3 CAPACITY

In the Transit Cooperative Research Program (TCRP) (Parkinson, 1996) 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. Fig.3.1 depicts a simplified formulation of line capacity.

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

Figure 3.1 Simplified line capacity formulation (Parkinson, 1996)

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

$$\text{Line Capacity, C} = 1440/(T + t) \times E \tag{3.1}$$

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 (UIC, 2004) determines line capacity using the reciprocal of average headway between two successive trains as follows:

$$Capacity = \frac{TimePeriod}{MinimumHeadway} \tag{3.2}$$

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 (Hansen. & Pachl., 2014). Calculation of T_{BL} considers a number of factors as follows (Pachl, 2002):

$$T_{BL} = tfc + wt + \frac{BL}{V} + \frac{l}{V} + rt + ct \tag{3.3}$$

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)

Fig.3.2 depicts this relationship graphically.

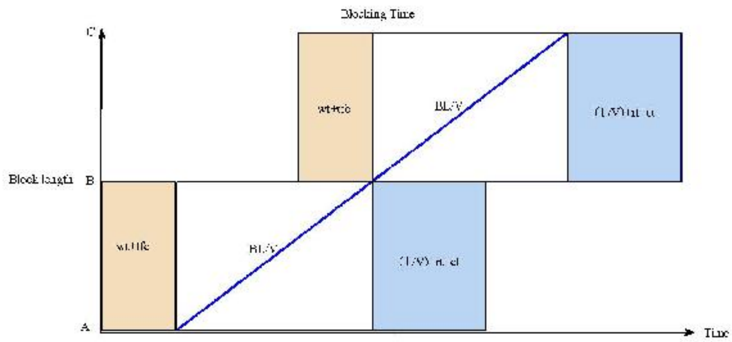


Figure 3.2 Blocking time

3.4 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 (Heydar, Petering, & Bergmann, 2013). Blocking time stairways (Hansen. & Pachl., 2014) 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 (Goverde, Corman, & D'Ariano, 2013). Fig.3.3 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.

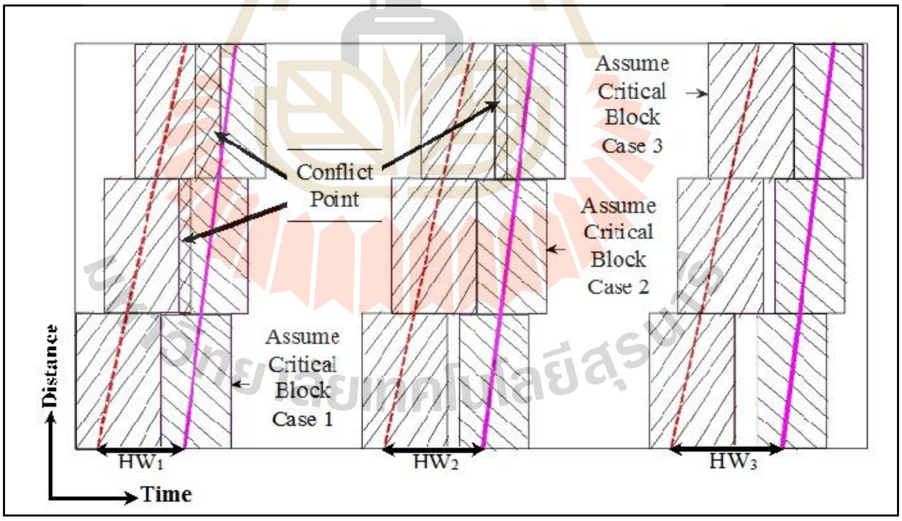


Figure 3.3 Critical block determination

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 $V_i < V_j$.

3.4.1 Equal block length: $BL_1=BL_2=BL_3=BL_4=BL_5$

Fig. 3.4–3.6 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.

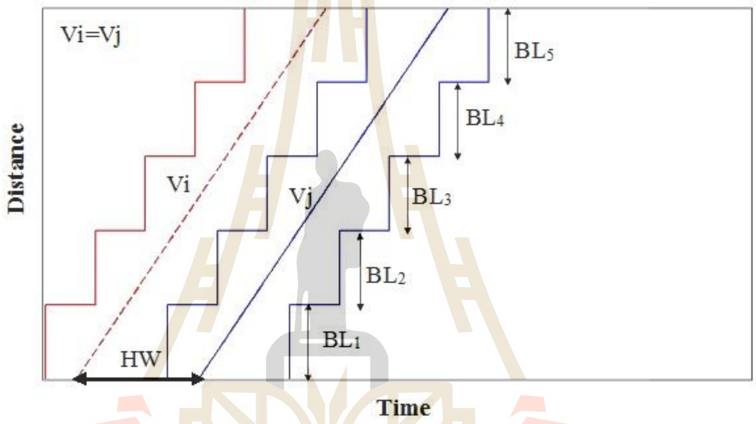


Figure 3.4 Time–distance diagram for equal block lengths when $V_i = V_j$ (Case 1-1)

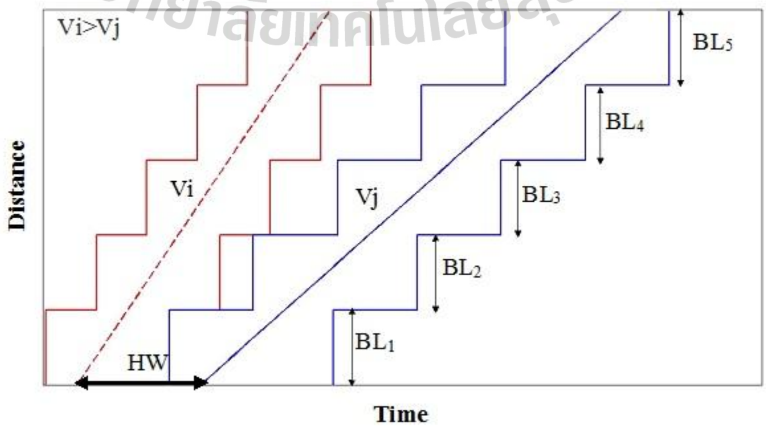


Figure 3.5 Time–distance diagram for equal block lengths when Vi > Vj (Case 1-2)

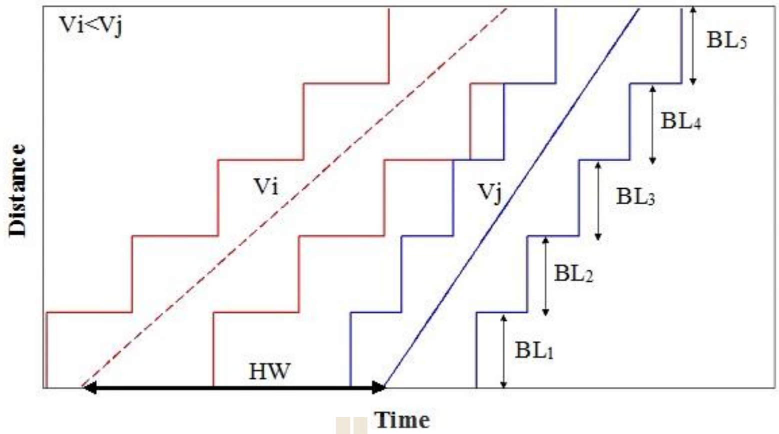


Figure 3.6 Time–distance diagram for equal block lengths when Vi < Vj (Case 1-3)

Fig.3.4 and Fig.3.5 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. Fig.3.6 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:

$$HW = \frac{BL + l}{V_i} + T_{FB} \qquad \text{when } V_i \geq V_j \tag{3.4}$$

$$HW = \frac{nBL + l}{V_i} - \frac{(n-1)BL}{V_j} + T_{FB} \qquad \text{when } V_i < V_j \tag{3.5}$$

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

3.4.2 Unequal block length: $BL_1 \neq BL_2 \neq BL_3 \neq BL_4 \neq BL_5$

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 3.1 summarizes the block lengths.

Table 3.1. 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

Fig. 3.7–3.9 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.

Fig. 3.7 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:

$$\mathrm{HW} = \frac{\mathrm{BL}_{\max}}{\mathrm{V}_{\mathrm{i}}} + \frac{l}{\mathrm{V}_{\mathrm{i}}} + T_{FB} \tag{3.6}$$

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.

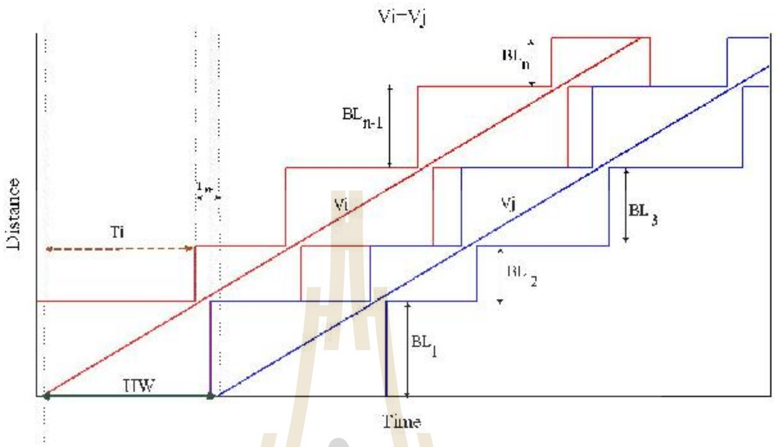


Figure 3.7 Time–distance diagram for unequal block lengths when $V_i = V_j$ (Case 2-1)

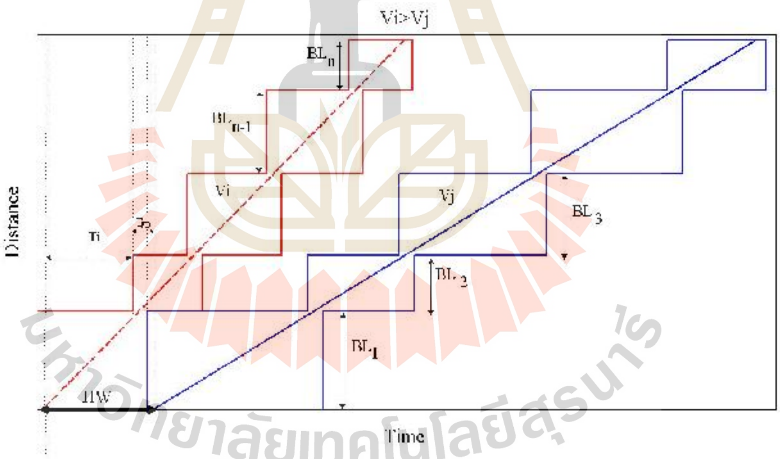


Figure 3.8 Time–distance diagram for unequal block lengths when $V_i > V_j$ (Case 2-2)

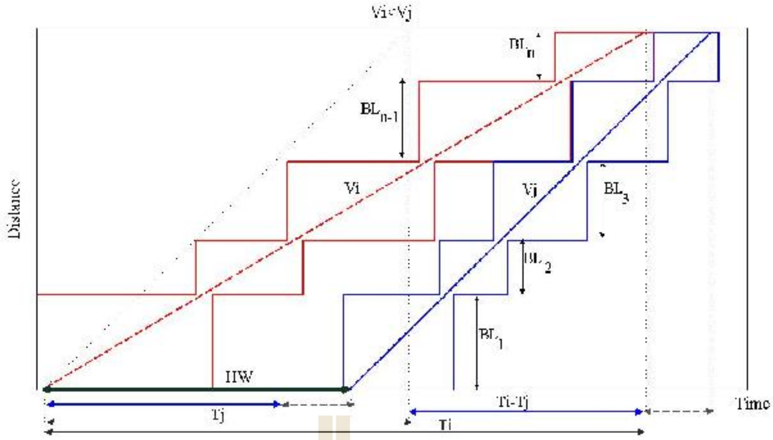


Figure 3.9 Time–distance diagram for unequal block lengths when $V_i < V_j$ (Case 2-3)

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

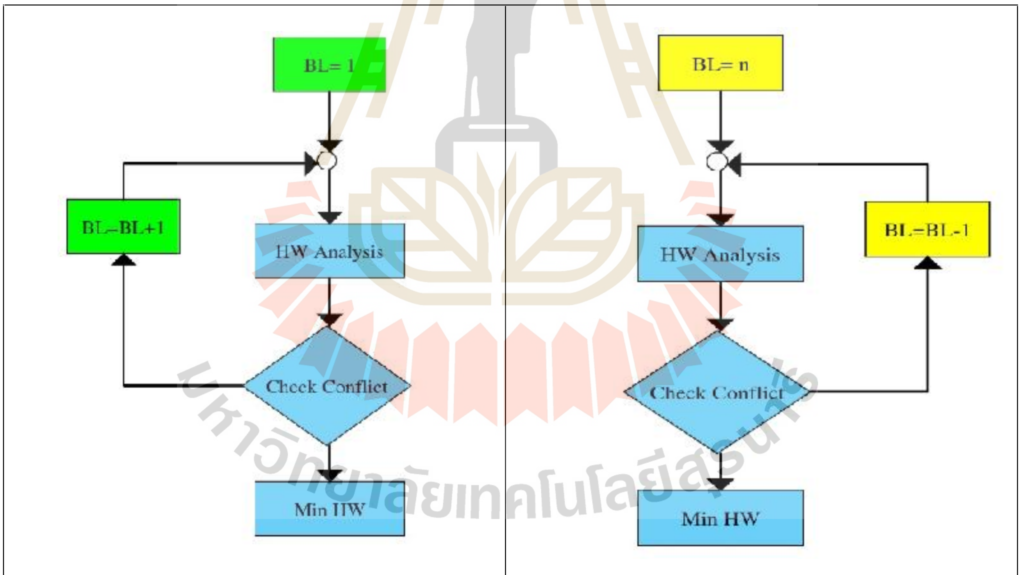
- When $V_i > V_j$, the critical block length is the first block and
- When $V_i < V_j$, the critical block length is the last block.

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.

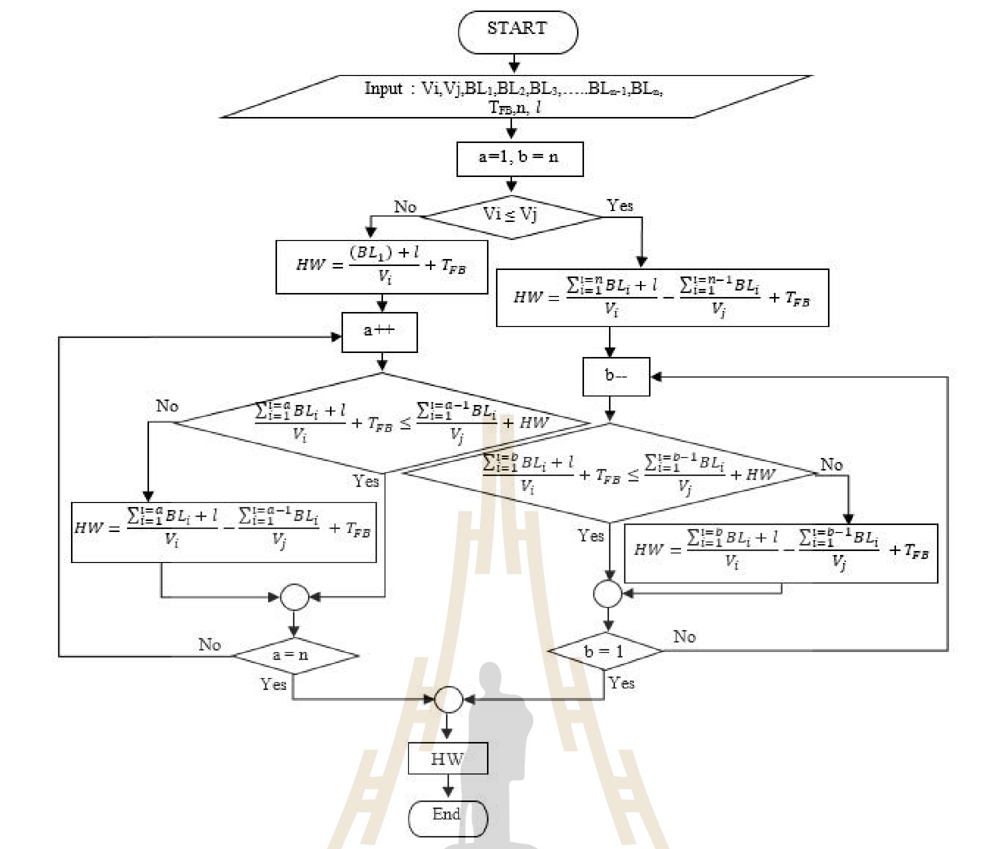
Fig. 3.9 depicts the time-space diagram in which the critical block is the last block. In this case, the fourth of five total blocks was sufficiently long to warrant critical block designation. To prevent any conflict, all block lengths were considered hierarchically. The block lengths from each of the three cases of operation were checked sequentially. The minimum headway is the safe design headway and is determined as follows:

$$HW_n = \frac{l_i + \sum_{\substack{z=1 \\ 1\le k\le n \\ k\in \text{int}}}^{z=k} BL_i}{V_i} + \frac{\sum_{\substack{z=1 \\ 1\le k\le n \\ k\in \text{int}}}^{z=k-1} BL_i}{V_j} + T_{FB} \tag{3.7}$$

Fig.3.10 depicts the stepwise process for determining a safe headway based on speed and distance along the rail line



(a) Case Vi ≥Vj (b) Case Vi<Vj



(c) Detail Combined Analysis

Figure 3.10 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 (Abril et al., 2008):

$$C = \frac{T - \frac{\sum_{i=1}^{i=n} BL_i}{V_i}}{HW_i + HW_j} + \frac{T - \frac{\sum_{i=1}^{i=n} BL_i}{V_j} - HW_i}{HW_i + HW_j} \quad (3.8)$$

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, Fig.3.11 shows five pairs of trains with $V_i < V_j$ completely passing through a five-block section in one hour.

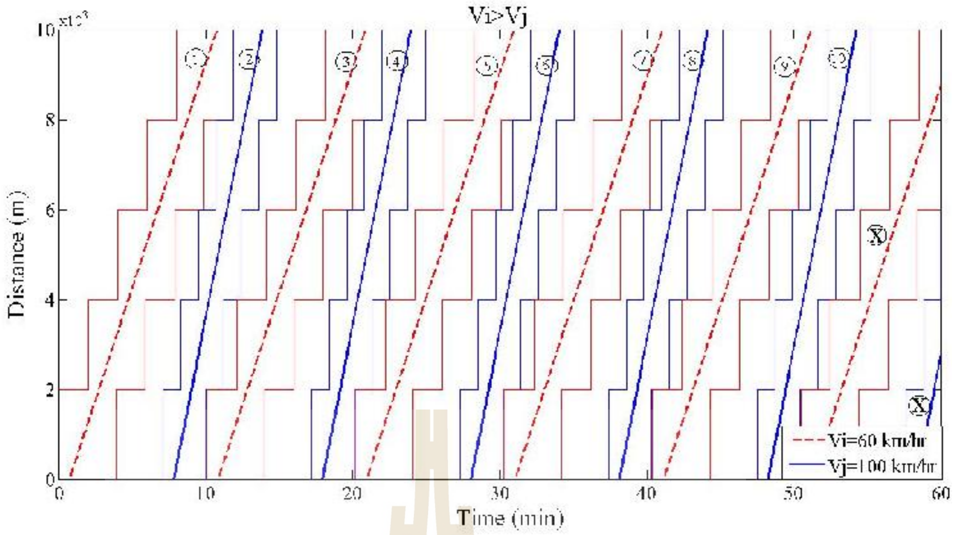


Figure 3.11 Number of trains completely passing through a section in a specified period

3.5 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.

3.5.1 Headway and capacity

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

Fig. 3.12 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. Fig. 3.12 (c–d) indicates that different headways should be assigned to achieve higher train flow. The stepwise process outlined previously in Fig. 3.10 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 (3.7) can be applied to short sections under five blocks; longer sections can be analyzed using the stepwise process outlined previously in Fig.3.10

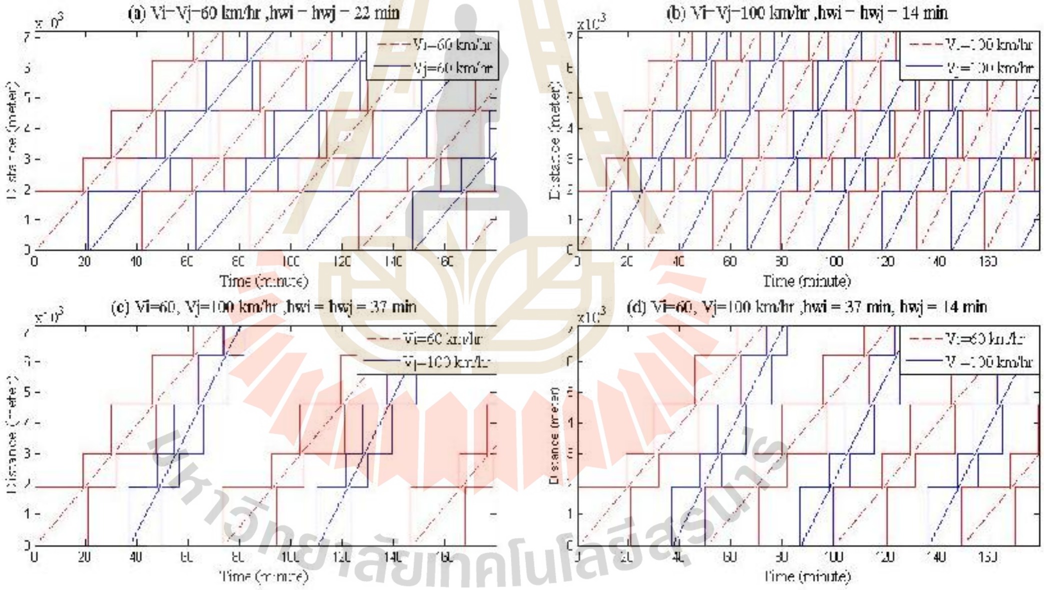


Figure 3.12 Time–space diagrams showing headways under various operational scenarios

3.5.2 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. Fig.3.13 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.

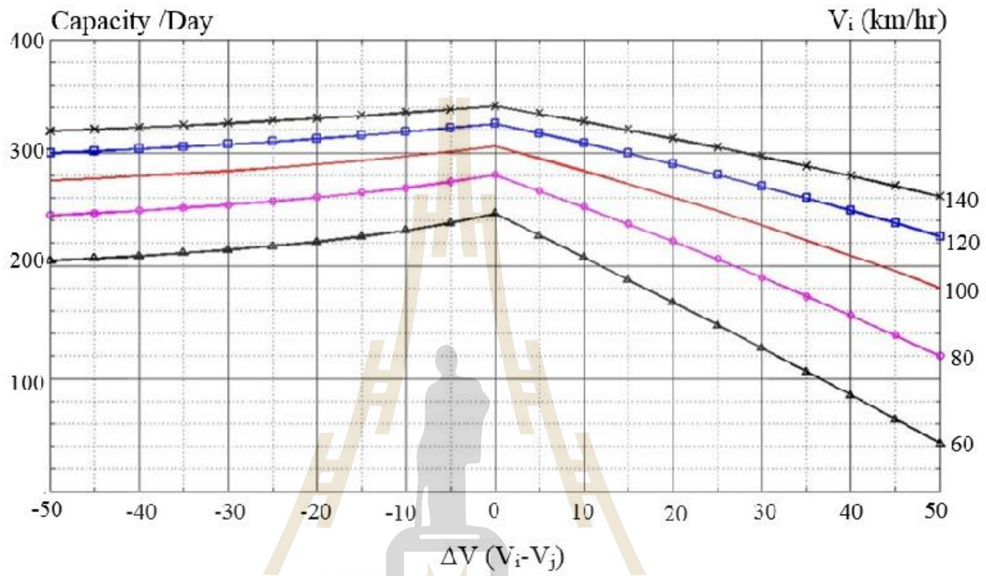


Figure 3.13 Relationship between Speed Difference and Line Capacity

3.5.3 Block length and capacity

Fig.3.14 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 (Liu, Mao, Wang, Du, & Ding, 2011; Parkinson, 1996). The suggested minimum block length is 1.5 times the braking distance (Profillidis, 2006). 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.

Fig. 3.15 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.

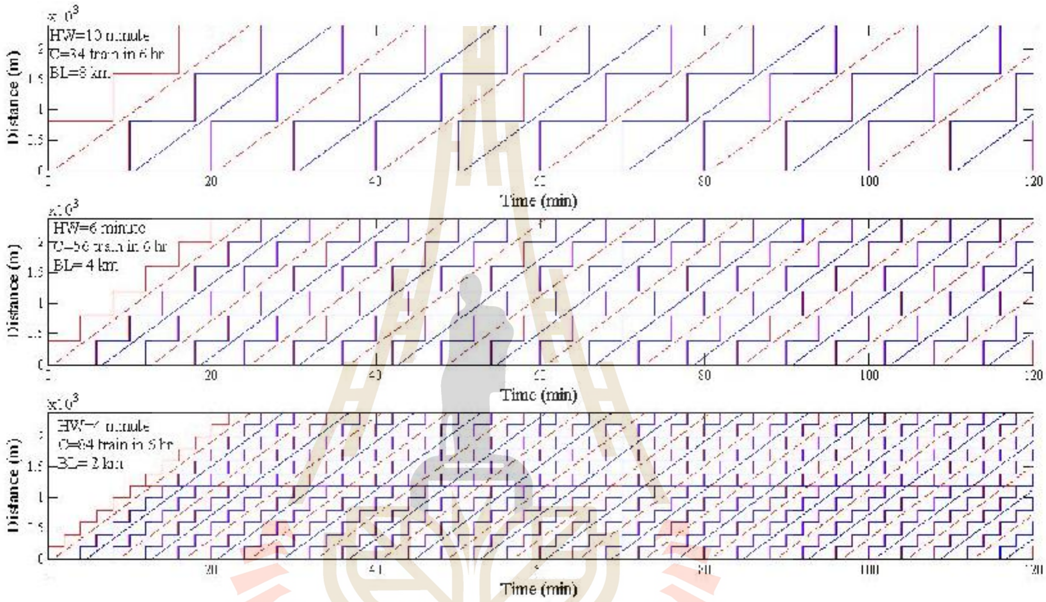


Figure 3.14 Time–distance diagram for different block length scenarios

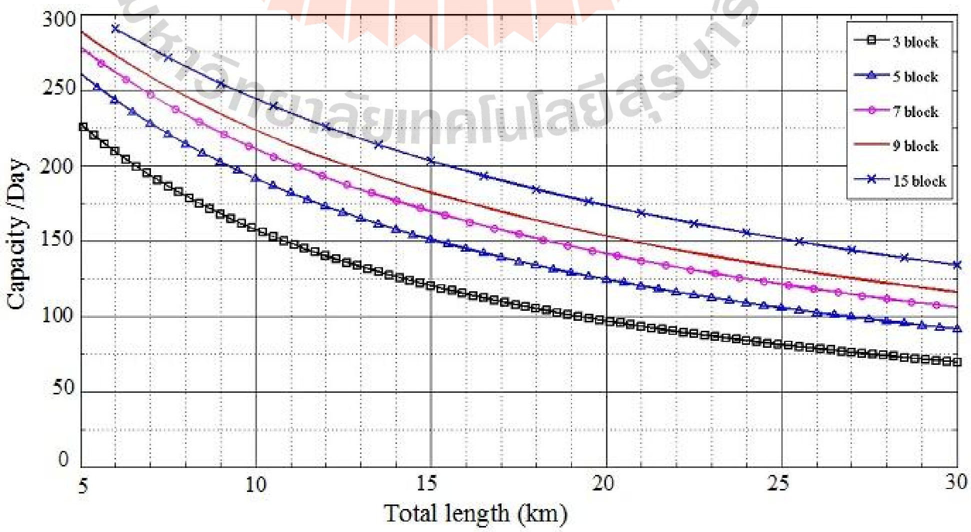


Figure 3.15 Relationship between number of blocks and line capacity

3.6 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 (Mitra, Tolliver, & Mitra, 2010). Other variables previously found to affect headways included train length (Banks, 2002); block length (LEE, 1997); the ratio of the summation of train length, block length, and stopping distance to speed (Landex & Kaas, 2005); and the ratio of train length to speed (Mao, Liu, Ding, Liu, & Ho, 2006). As block length decreases, capacity increases (Dicembre & Ricci, 2011). 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.

3.7 ACKNOWLEDGEMENT

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CHAPTER IV

ANALYSIS AND DESIGN OF NOMOGRAPHS FOR MINIMUM HEADWAY CALCULATION

4.1 ABSTRACT

This study proposes the design and analysis of nomographs for minimum headway calculations using critical blocks to reduce the complexity of mathematical equations. For trains with different speeds, block overlapping should be checked forward or backward in a looping manner, while nomographs simplify the analysis and eliminate iterations. Nomographs for headway calculation are constructed using Python scripts in PyNomo software. The associated variables include train speed, train length, and block length. Three nomographs are designed for three types of operation: Model 1 for cases wherein two trains have equal speeds, Model 2 for those wherein the leading train is faster, and Model 3 for those wherein the leading train is slower. The validation reveals that the nomographs yield minimum headways that are close to the result obtained by mathematical derivation. The data can be used to create a train schedule for safe operation without conflict.

4.2 INTRODUCTION

To maximize efficiency of train scheduling, the headways between the trains should be minimized (Fransoo & Bertrand, 2000; Li, Sheu, & Gao, 2014). Currently, the minimum headway can be determined using the block time model (de Fabris, Longo, Medeossi, & Pesenti, 2014; Fumasoli, Bruckmann, & Weidmann, 2015; Landex & Kaas, 2005; Medeossi, Longo, & de Fabris, 2011; Parkinson, 1996). This model can be used for trains with equal (Lindner, 2011) and unequal (Harrod, 2009; Huisman & Boucherie, 2001) speeds. The key variables affecting the headway are train lengths (Banks, 2002; Mao, Liu, Ding, Liu, & Ho, 2006), block length (Abril et al., 2008; Dicembre & Ricci, 2011; Landex & Kaas, 2005; C.-K. LEE, 1997; Liu, Mao, Wang, Du, & Ding, 2011; UIC, 2004), and speed (Mitra, Tolliver, & Mitra, 2010).

The Determination of the minimum headway should consider the critical block, which is the block that defines a safe minimum headway (Goverde, Corman, & D'Ariano, 2013). A time–distance diagram may be used to classify train operation and determine the effects of speed, train length, and block length upon the critical block. The analysis should be divided into two cases: equal and unequal block lengths. For unequal block lengths, when the train speeds are equal, the longest block will be the critical one. If the train speeds are different, minimum headway determination becomes more complex as and looping processes are required to check key conditions.

Nomograms or nomographs are designed using a graphical form to analyze and present the results (Cantinotti et al., 2016; Gluchoff, 2012; Lu, Huang, & Zhang, 2016). A nomograph is normally constructed to determine solutions under various cases (Auerswald, Fiener, Martin, & Elhaus, 2014) and forecast results. They have been widely used, particularly in the medical field (Kawai et al., 2015; C. K. Lee et al., 2015; Morris et al., 1993; Samplaski et al., 2014) and constitute an extremely useful tool for solving repetitive problems that might otherwise require complex mathematical equations (Bandyopadhyay, 1983; Thananitayaudom, 1977) they are flexible for various applications.

This research constructs graphical nomography tools as a prototype solution for reducing complexity and determining minimum headway assuming key relevant factors, including train length, block length, and speed. This research focus partiality on unidirectional operation with equal and unequal block lengths.

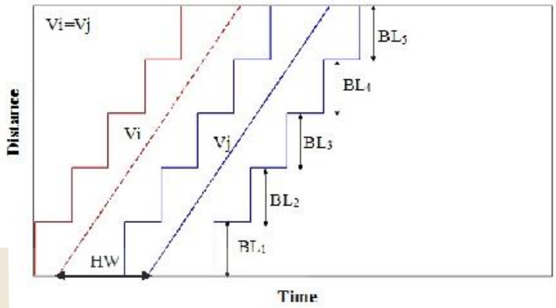
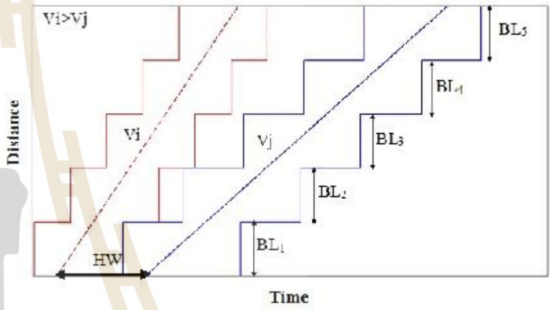
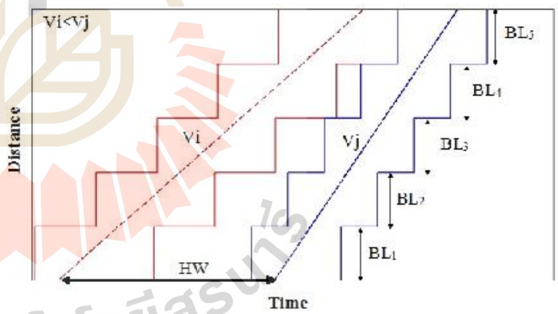
4.3 BLOCKING TIME

Time headway is a key measure in determining line capacity and establishing the timetable. Time headway has defined the difference between the time when the front of a train arrives at a point on the track and the time the front of the next train arrives at the same referenced points on both trains.

The analysis is of time headway can be classified into equal and unequal block length scenarios. This analysis should consider the critical block length that defines minimum headway and maximum capacity without conflict at any location. The time spent in the critical block comprises running time, signal-watching time (wt), clearing time in signal (tfc), and release time (rt). The combination of these components is known as blocking time (de Fabris et al., 2014; Hansen. & Pachl., 2014; Medeossi et al., 2011; Pachl, 2002).

The headway analysis starts with assigning a speed Vi for the first train and Vj for the second on a route with n blocks. Only one train can enter a block at a given time. The analysis comprises two cases: trains with same speeds or Vi = Vj (Lindner, 2011) and trains with different speeds or Vi > Vj and Vi < Vj (Hernando, Roanes-Lozano, & García-Álvarez, 2010; Huisman & Boucherie, 2001; Kanai, Shiina, Harada, & Tomii, 2011; Mussone & Wolfler Calvo, 2013; Vromans, Dekker, & Kroon, 2006). The time–distance diagram in Table 4.1 shows the operation under equal block length conditions and the effects of the number of trains, order, block length, and speed difference on the critical block.

Table 4.1 Determination of Headway under Equal Block Length Operation.

Type	Formula	Time–Distance Diagram
Vi=Vj	$\dfrac{BL+l_i}{V_i}+wt+tfc+ct+rt$	
Vi>Vj	$\dfrac{BL+l_i}{V_i}+wt+tfc+ct+rt$	
Vi<Vj	$\dfrac{nBL+l_i}{V_i}+T_{FB}-\dfrac{(n-1)BL}{V_j}$ $T_{FB}=wt+tfc+ct+rt$	

Where

V_i	=speed of train i	V_j	=speed of train j
BL	= Block length	n	= number of blocks
l	= Train length	ct	= Clearing time in the block
rt	= Release time	wt	= Signal watching time
tfc	= Signal clearing time		

When the block lengths are different, headway analysis becomes more complicated. A hierarchical check is required to prevent conflicts. Complex mathematical models take into account train speed, train length, and block length in determining minimum headway. Figure 4.1 shows a diagram explaining the steps for identifying the critical block and determining the safe minimum headway.

This study presents the design of a prototype nomograph to facilitate calculation under all conditions. This nomograph uses the PyNomo program, powered by Python script. To create nomographs, 10 forms of equations are normally applied depending on the relationship of sub-equations $F_i(u_i)$. Four forms have been selected to calculate the minimum headways in this study, as shown in Table 4.2 Nomographs are constructed following the procedures given in Figure 4.1

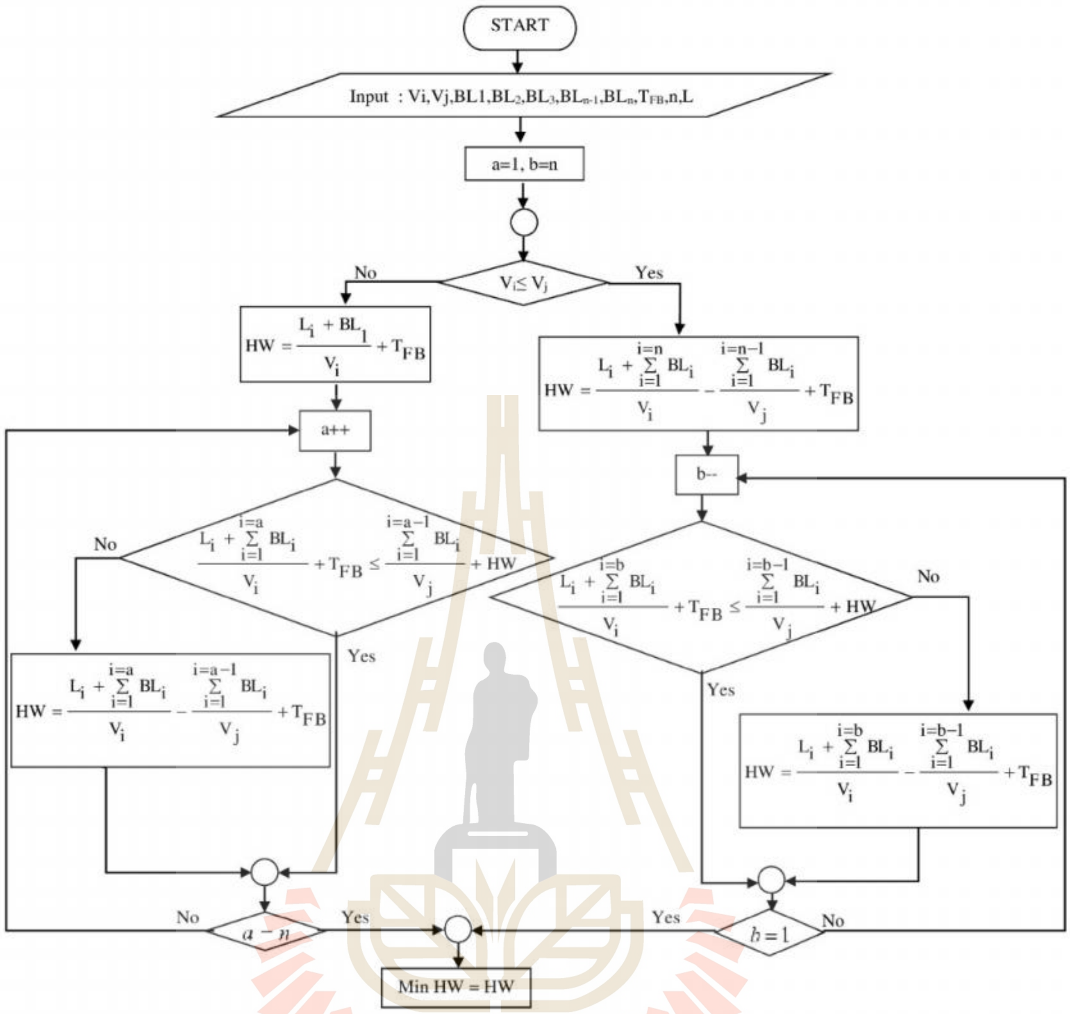


Figure 4.1 Headway Determination Diagram

Table 4.2 Types of Nomographs Supported by PyNomo

Type	Form of Equation	Form of Nomogram
Type 1	$F_1(u_1) + F_2(u_2) + F_3(u_3) = 0$	Three parallel lines
Type 2	$F_1(u_1) = F_2(u_2)F_3(u_3)$	Left-tilting “N” or right-tilting “Z”
Type 3	$F_1(u_1) + F_2(u_2) + \cdots + F_N(u_N) = 0$	N parallel lines with reference axes
Type 6	$F_1(u_1) = F_2(u_2)$	Scale transforming “Ladder”

4.4 RESEARCH METHOD

Nomographs use lines to represent variables and distances between lines and scale to represent the relation between variables affecting headway. The ranges on scales are designed to cover the train and track characteristics. These nomographs are flexible. Therefore, they can be applied to various cases of operation, including changes in route or speed characteristics.

The research method involve developing practical nomographs for train minimum headway determination. The result from the nomograph are validated with analytical solution to confirm its accuracy. The research framework is illustrated in Figure 4.2

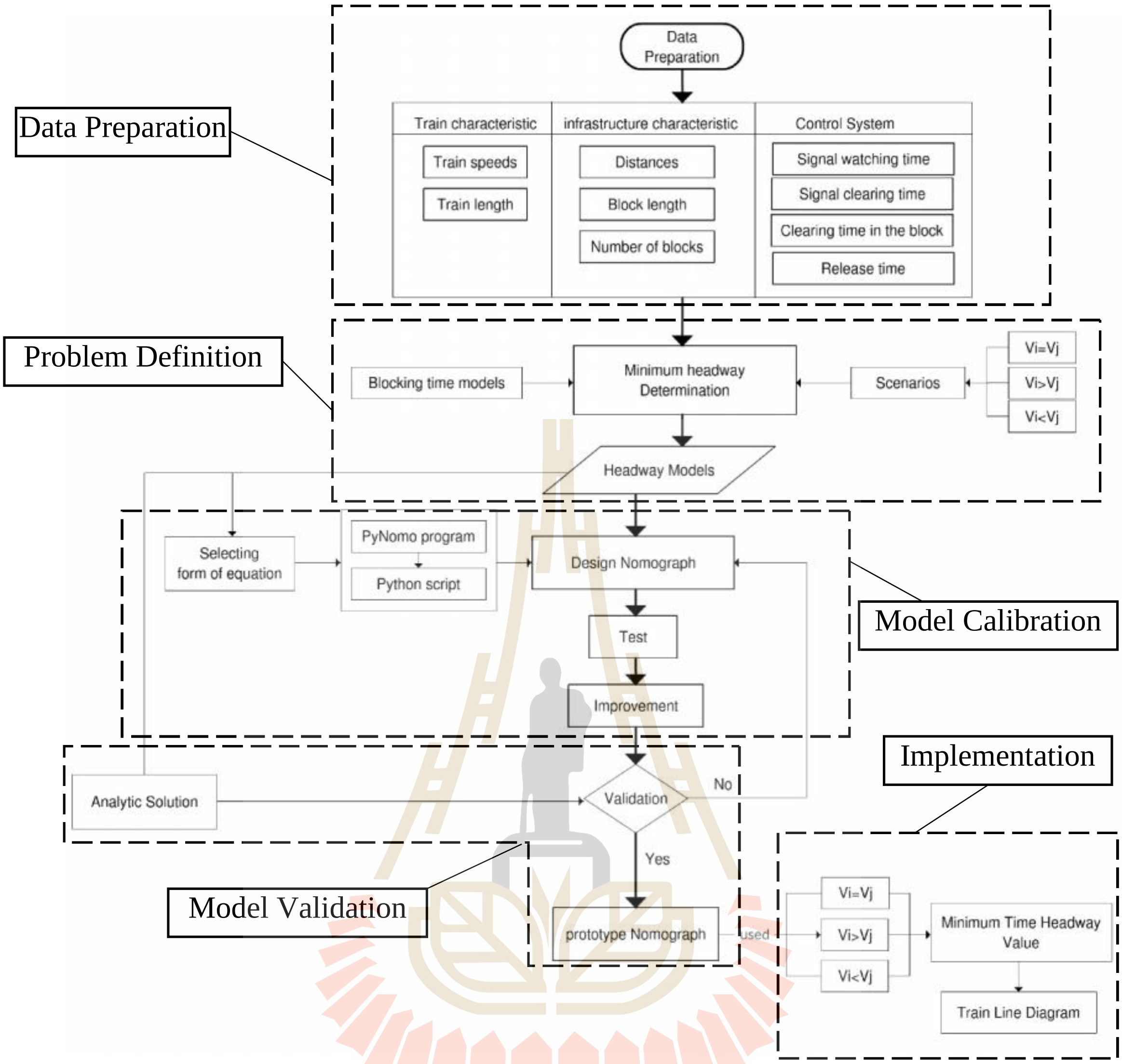


Figure 4.2 The conceptual framework diagram of analysis and design of nomographs for minimum headway calculation.

4.4.1 Model 1 for Vi = Vj

The nomograph in Figure 4.4 is designed based on the critical block determined by maximum block length. This nomograph can be applied to a maximum block length of 70 km, with speeds of 50–150 km/hr. It is suitable for Vi = Vj on routes with equal and unequal block lengths. The following data are required:

- Distance from the origin station to the end of the longest block (D_{bmax}) km, where $D_{b\max} = \sum_{i=1}^{k} BL_i$ and k is the position of maximum block length (Figure 3 shows an example of calculating D_{bmax})
- Maximum block length, BL_{max} (km)
- Train length, L (m)
- Leading and following train speeds, Vi and Vj (km/hr), respectively
- Signal-watching time and clearing time in signal plus the release time and clearing time in block, T_{FB} (min) = $wt + tfc + rt + ct$

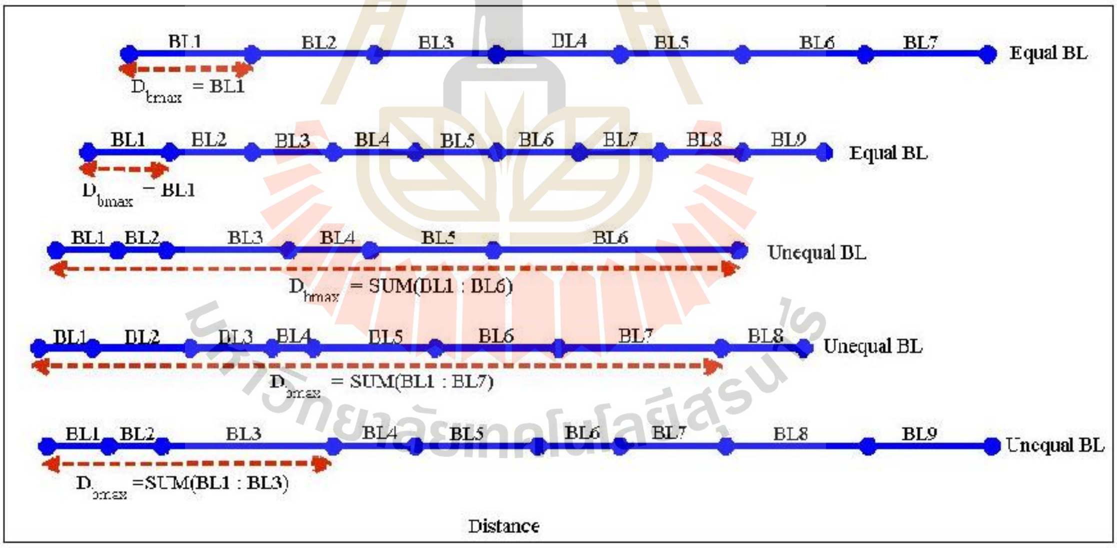


Figure 4.3 D_{bmax} Calculation Example

4.4.2 Model 2 for Vi > Vj

The nomograph in Figure 4.5 is designed under the assumption that the leading train is faster. The trailing train can be released after the leading train has left the block. Thus, the first block becomes the critical block. This nomograph can be applied to block lengths of up to 10 km with speeds of 40–140 km/hr. It requires three line connections among the graphs and is suitable for operations under Vi > Vj with equal and unequal block lengths. The following data are required:

- The first block length, BL_1 (km)
- Train length, L (m)
- Leading train speed, Vi (km/hr)
- T_{FB} (min)

4.4.3 Model 3 for Vi < Vj

The nomograph in Figure 4.6 is designed for headway determination when the leading train is slower. Thus, the last block normally defines the critical block unless the blocks have significantly different lengths. The following train has to wait until the leading train arrives at the last block before being safely released from the origin station. This nomograph can be used for route lengths of up to 100 km with speeds of 50–150 km/hr and it is suitable for operations under Vi < Vj. The following data are required:

- Distance from origin to destination (D_n) (km) = $\sum_{i=1}^{i=n} b_i$
- Train length, L (m)
- Train speeds, Vi, Vj (km/hr)
- T_{FB} (min)

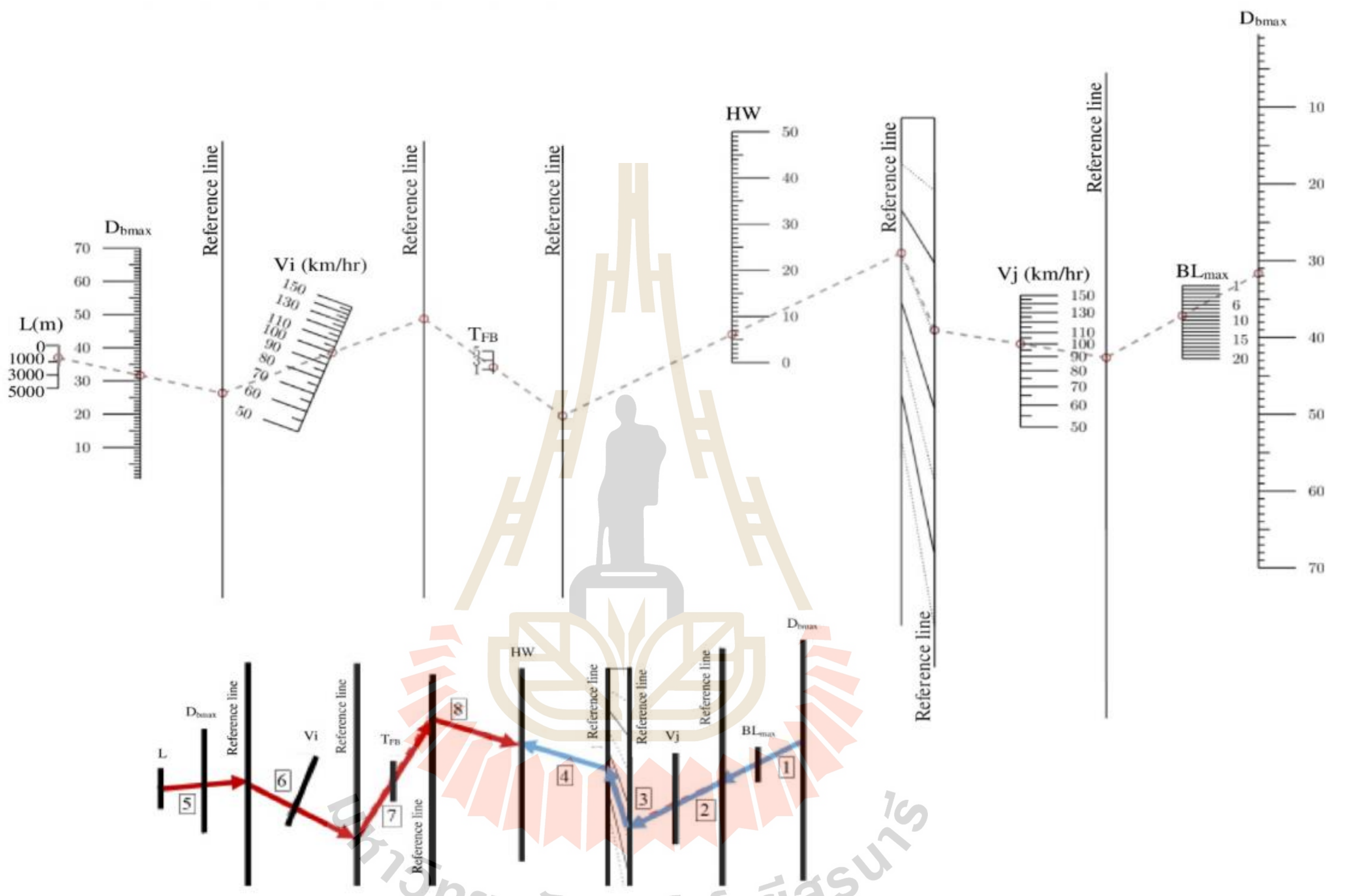


Figure 4.4 Nomograph Model 1 for Vi = Vj

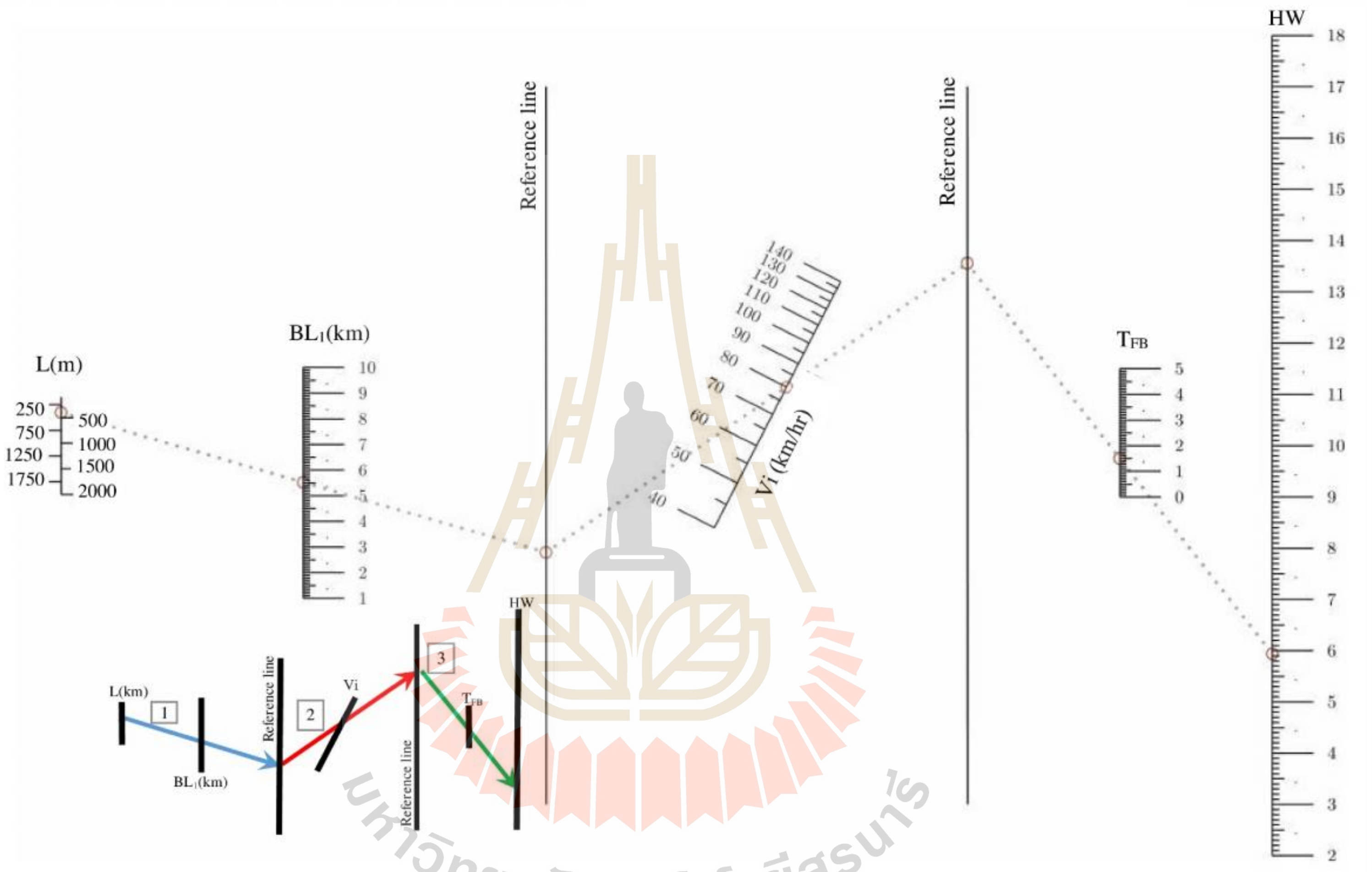


Figure 4.5 Nomograph Model 2 for Vi > Vj

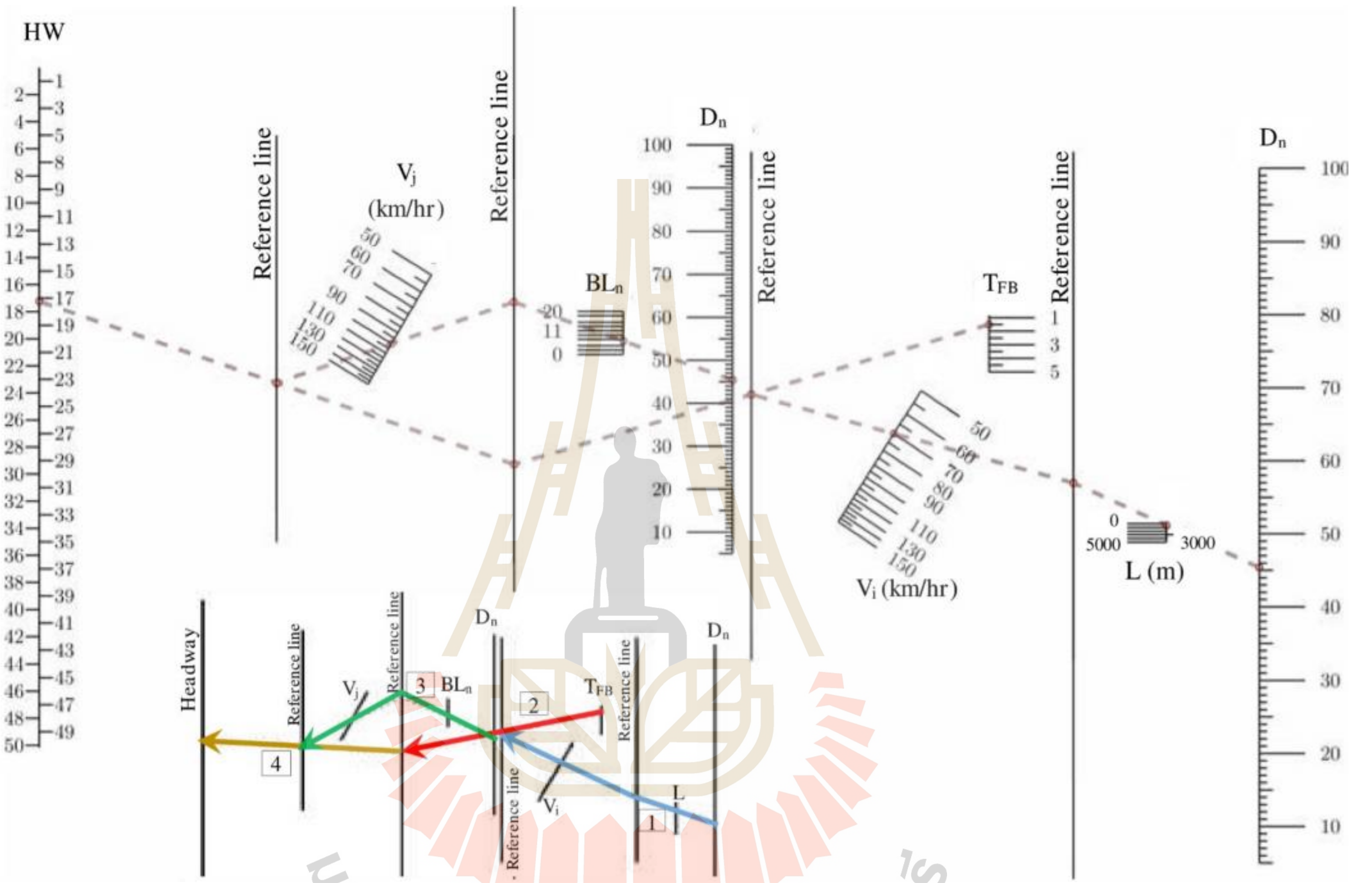
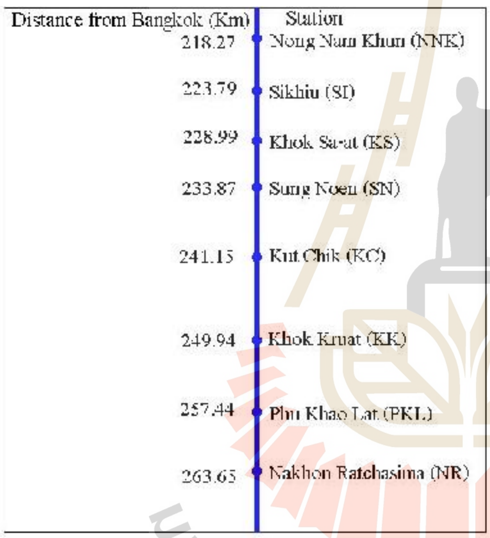


Figure 4.6 Nomograph Model 3 for Vi < Vj

4.5 RESULTS AND DISCUSSION

The nomographs are validated for a route with unequal block lengths using real distance data from the Nong Nam Khun (NNK)–Nakhon Ratchasima (NR) section of the State Railway of Thailand (SRT) Northeastern Line. The section comprises eight stations spanned across a total of 45.38 km. A block covers the distance between two adjacent stations. Thus, the block lengths in this section are different, as shown in Figure 4.7 (a).



Origin	Destination	No. BL	BL (km)
NNK	SI	BL_1	5.52
SI	KS	BL_2	5.2
KS	SN	BL_3	4.88
SN	KC	BL_4	7.28
KC	KK	BL_5, BL_{max}	8.79
KK	PKL	BL_6	7.5
PKL	NR	BL_7, BL_n	6.21

a) Nong Nam Khun (NNK)–Nakhon Ratchasima (NR) Blocks

Case	Vi	Vj	Model	BL_1	BL_5,BL_{max}	BL_7, BL_n	D_{bmax}	D_n	HW (Min)
1	60	60	1	-	✓	-	✓	-	11
2	100	100	1	-	✓	-	✓	-	7
3	80	60	2	✓	-	-	-	-	6
4	100	80	2	✓	-	-	-	-	5.1
5	60	80	3	-	-	✓	-	✓	18
6	60	100	3	-	-	✓	-	✓	24

b) Headway Calculation from Various Scenarios

Figure 4.7 Headway Calculation by Nomography

4.5.1 Nomography Application

The validation is conducted with 60, 80, and 100 km/hr speeds for the Vi = Vj, Vi < Vj, and Vi > Vj cases, assuming a train length (L) of 400 meters and T_{FB} = 1.5 min. A total of 6 cases are tested with combinations of speeds and other variables, as shown in Figure 4.7 (b).illustrate the determination of the headway using nomographs.

4.5.2 Operations on a Time–Space Diagram

The nomographs are validated with time–space diagrams using the blocking time on the studied route. Minimum headways obtained from the nomograph are used as initial headways between the two trains for all six cases as shown in Figure 4.8. Blocking stairways show that both trains can run together without any conflict. Therefore, the headway from the three nomographs can be assumed to be the minimum headway from the critical block consideration. No space is available for further headway reduction.

When two trains of different types alternately run on the route, the nomograph application should be divided into two parts to determine the two headways. For example, consider two trains running on the NKK–NR section with speeds of Vi = 60 km/hr and Vj = 100 km/hr. The first part of the headway between Train 1 and Train 2 can be determined using Model 3 as it is under the Vi < Vj condition, whereas the headway between Train 2 and Train 3 uses Model 2 as it falls in the range of Vj > Vi. The speed, Vj, is fixed at 100 km/hr. The train operation diagram is shown in Figure 4.9

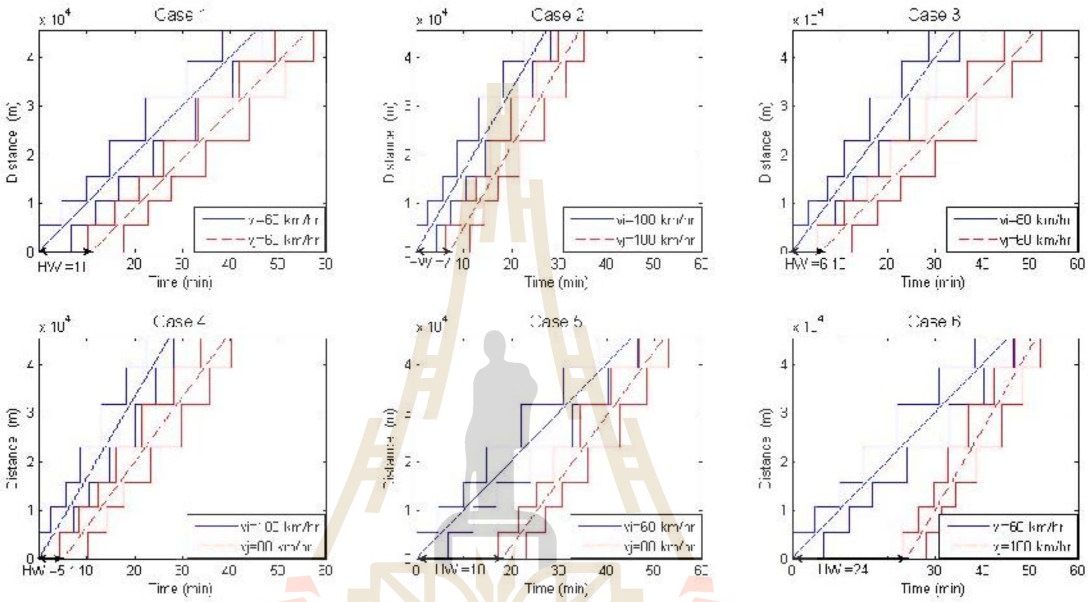


Figure 4.8 Blocking Time Stairway of Train for All Six Cases As Computed by Nomography

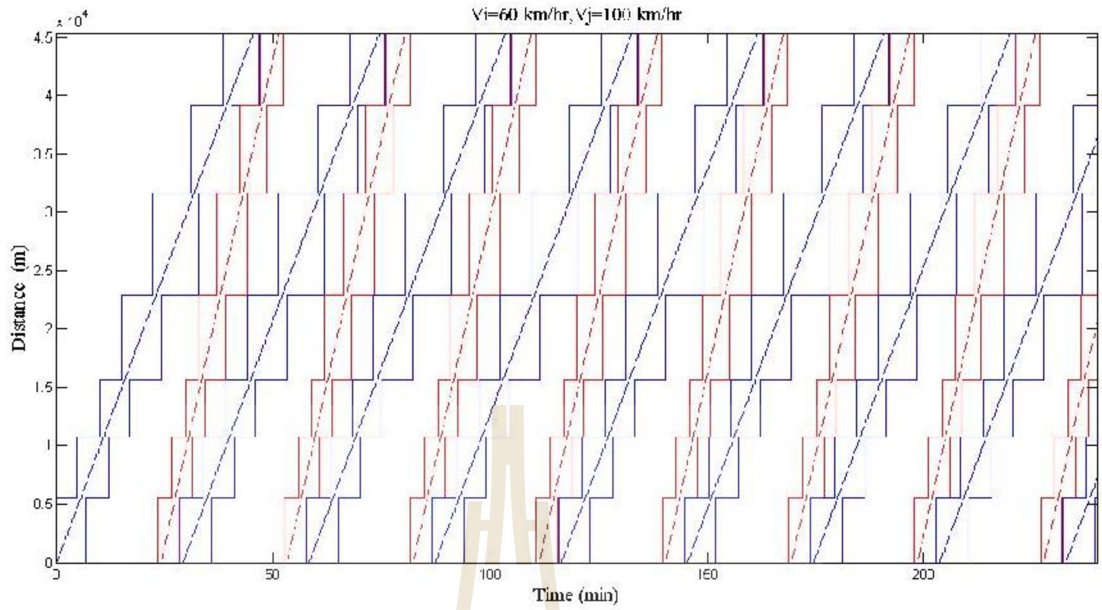


Figure 4.9 Time–Space Diagram for Two Types of Trains with Headway Calculated from Models 2 and 3

4.5.3 Nomography vs. Methematical Analysis

Headways calculated from the nomographs are close to those computed by mathematical equations. The differences are only in decimals. Nomographs can be used to effectively estimate headways in both equal and unequal block length cases. More variables, such as buffer time (Büker, 2013) and dwell time, can be added to T_{FB} or as additional lines to increase the efficiency of estimation. In the route where a given block length is more than 2.5 times the other and Vi ≠ Vj, it is recommended that the result be compared with that obtained using Model 1. One must compare headways from two nomographs and choose the larger value to prevent conflict. For example, when Vi > Vj, the maximum value of the headways obtained from Models 1 and 2 must be chosen, and when Vi < Vj, the maximum value of the headways obtained from Models 1 and 3 must be chosen.

4.6 CONCLUSIONS

Under operation with equal block lengths, the minimum headway can simply be determined by mathematical equations. When trains are running on different block lengths, the significant variables and conditions become more complicated. To determine the minimum headway, one must consider the hierarchy of conditions and may have to rely on a software package to determine the solution. The nomographs are validated, and it is proved that they yield results close to those obtained by mathematical analysis. In addition, the graphs are sufficiently flexible to be used for any type of operations, including trains with equal and unequal speeds on sections with equal and unequal block lengths.

However, this research designs the nomographs to be used as tools for quickly estimating the minimum headway and reducing the complexity of the analysis. In reality, train operation involves the variation of speeds at the shut, stop and between stations constrained by geometry. Further research could add acceleration, deceleration and other types of speed variation to better reflect real operating conditions. Interested individuals can adopt and enhance the use of nomographs in academic and practical analysis of railway projects.

Nomograph is a flexible tool that can be customized to solve various systems in the future. Including improved single and double-track railway operation. In can also serves as an effective analytical tools under scenarios with major and minor adjustments in the future systems.

4.7 ACKNOWLEDGMENTS

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CHAPTER V

ANALYSIS OF APPROPRIATE OVERTAKING POSITION UNDER EQUAL BLOCK LENGTHS

5.1 ABSTRACT

This paper studies train passing operation and determine line capacity by checking minimum headway. The analysis is based on the blocking time model displayed on the time space diagram where minimum headway and minimum waiting time are calculated. The study found that the capacity is affected by the number of blocks and the overtaking block position. The graph between the overtaking position and capacity is symmetrical, in which capacity is reducing when the overtaking position is far from the center of the line. The overtaking position that maximizes capacity is not affected by speed nor block length. In the case of even number of blocks, the appropriate location to overtake is (n / 2) +1 while in case of odd number of blocks, the overtake position is at (n+1)/2 and (n+3)/2. Both positions maximize the line capacity for each case. In addition, when the block length was reduced the capacity increased and decrease dwell time.

5.2 INTRODUCTION

Land transportation mode with the highest fuel efficiency is rail transport. It is 3.4-4.5 times more cost-effective than truck, 1.7-2.0 times cheaper than bus and 5.0 time cheaper than private car. It also releases lower greenhouse gas (Z. Wang, Chen, & Fujiyama, 2015). To cope with fuel crisis (Limanond, Jomnonkwao, & Srikaew, 2011; Travesset-Baro, Gallachóir, Jover, & Rosas-Casals, 2016), pollution (Ó Gallachóir, Howley, Cunningham, & Bazilian, 2009; Ratanavaraha & Jomnonkwao, 2015) and rapid increase in number of private cars (Mohamad & Kiggundu, 2007) governments in many countries set policies including car free day, car-restricted area (Nieuwenhuijsen & Khreis, 2016), public transport promotion campaign (C. B. Wang, Hokao, & Gao, 2011). Thai government also realizes and reacts on this concerns with focus on railway utilization. A large part of Thailand's railway network consists of single track sections. It provides low capacity due to limitations in passing and overtaking. The government recently initiated a double track program to increase capacity, shorten travel time and save the fuel energy used in transportation. Nonetheless double track construction requires high investment and takes a long time to implement. In the meantime, researches focuses on optimizing train schedule to accommodate trains on single track (Li, Sheu, & Gao, 2014). Some routes has successfully developed timetable for single track and accommodate a large number of passengers despite no investment for track doubling (Castillo, Gallego, Ureña, & Coronado, 2011).

Single track operation for trains with small speed difference will result in high capacity (Mitra, Tolliver, & Mitra, 2010). In reality, due to marketing reasons, passenger and freight trains must spread out operations to cover the whole 24-hour period. Slow and fast trains often run alternately. Timetabling must provide overtaking spots to increase the network capacity. This research explores the minimum headway for overtaking at different positions. It varies train speeds to determine relationship among overtaking position versus minimum headway, dwell time, and capacity. The best overtaking position will maximize the line capacity and best utilize single track infrastructure under given block length and schedule train speeds.

5.3 LITERATURE REVIEW

Researchers have employed many scheduling techniques to enhance utilities of the infrastructure. Previous studies include optimal rescheduling (Espinosa-Aranda & García-Ródenas, 2013; Törnquist & Persson, 2007) increase service frequency on single-track (Coviello, 2015), double-track (Xu, Li, & Yang, 2016) and mixed networks (Gao, Kroon, Schmidt, & Yang, 2016). These scheduling techniques take into account constraints on time components including departure time, running time, dwell time, and headway.

Single track scheduling normally focus on trains running in the same direction. The techniques include moving trains (Šemrov, Marsetič, Žura, Todorovski, & Srdic, 2016), adjusting time to enter the network (Carey & Carville, 2003) meet and pass at stations (Zhou & Zhong, 2007), and overtaking train by avoiding schedule conflicts (Pouryousef, Lautala et al. 2016), passing scheme where faster train gets priority (Dündar & Şahin, 2013; Heydar, Petering, & Bergmann, 2013; Kanai, Shiina, Harada,

& Tomii, 2011; Krasemann, 2015), delaying slower trains at the station to accommodate faster ones (Barber et al., 2004; Chiang, Hau, Ming Chiang, Yun Kob, & Ho Hsieh, 1998)

The change of the conflict position influences the delay of the trains (Li, Gao, Li, & Yang, 2008). Brucker, Heitmann and Knust find an optimal schedule with the minimal delay (Brucker, Heitmann, & Knust, 2002). A different technique mainly focuses on reducing the running time per track section of different trains along a railway line (Vromans, Dekker, & Kroon, 2006). Another study focused on minimizing the length of the dispatching cycle and minimizing the total stopping (dwell) time (Heydar et al., 2013). Optimization models are also used train scheduling problem of minimizing passenger waiting time (Niu, Zhou, & Gao, 2015).

Most researches go through trial and error process to determine the highest capacity or minimum safe headway. On the contrary, this research uses true minimum headway from blocking diagram model (Hansen. & Pachl., 2014) which vary by type of train, block length, and train length. It focuses on two types of train running alternately and in which faster passing slower trains. Minimum headway and dwell time are then determined from various passing scenarios.

5.4 MATERIALS AND METHODS

5.4.1 Minimum Headway Analysis

Railway network capacity refers to the maximum number of trains passing a point in a given time period. It reflects rail service efficiency (UIC, 2004).

The capacity greatly depends on train scheduling. The number of trains can be calculated from the reciprocal of average train headways. To increase capacity one needs to minimize the headway to the value by which train can follow one another safely under conditions of train speeds and block time model (Büker, 2013; de Fabris, Longo, Medeossi, & Pesenti, 2014; Fumasoli, Bruckmann, & Weidmann, 2015; Hansen. & Pachl., 2014; Landex & Kaas, 2005; Medeossi, Longo, & de Fabris, 2011; Pachl, 2002). Normal operating rule allows only one train to occupy a block to avoid conflict. Minimum headway analysis depends on determining blocking time which consists of running time, additional time need to clear the train and block. This clearance time consists of signal watching time (wt), clearing time in signal (ct), clearing time in block and release time (rt). Given V_i and V_j are the speeds of leading and following trains, the minimum headway analysis will consider three scenarios in which $V_i=V_j$, $V_i>V_j$ and $V_i<V_j$.

When the faster train follows the slower one, the minimum headway is larger than the other two cases. To avoid conflict, the fast train has to wait until the slow train reaches the destination and is taken out of the network. This research aims to minimize the headway when $Vi<Vj$ to increase capacity and to determine the position that the conflict is most likely to occur. This position depend largely on speed difference (Törnquist & Persson, 2007) and block length. this study assumes that the faster train only pass the slow train once at a chosen location to minimize stops for the slow train (Goverde et al., 2016). Headway and dwell time can be determined from relationship between distance and train speeds on the critical block section (Goverde, Corman, & D’Ariano, 2013). If the passing occurs at block 3 (m=3)

and block 4 (m=4) on a five-block section, the minimum headway can be calculated as shown in Equation 5.1-5.6.

From relationship between overtaking position, speeds and block length in Figure 5.1, headway and dwell time for Trains *i* and *j*, when passing at *m*=3, can be determined as follows:

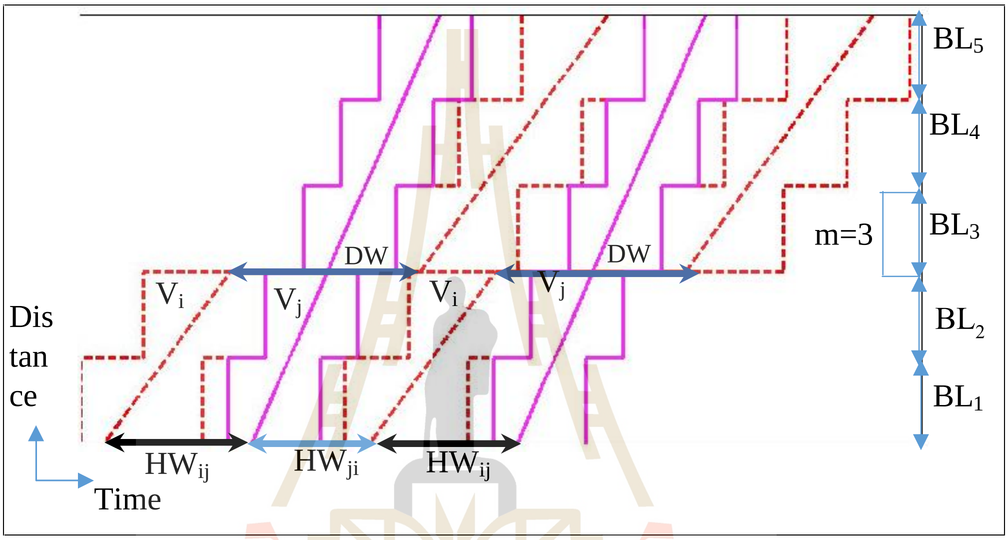

Figure 5.1 Time Space Diagram for Train *i* passing Train *j* in block 3

m=3

$$HW_{ij} = \frac{BL_1 + l_i}{V_i} + T_{FB} \tag{5.1}$$

$$DW_i = \frac{2BL + l_j}{V_j} - \frac{BL}{V_i} + T_{FB} + HW_{ij} \tag{5.2}$$

$$HW_{ji} = \frac{BL}{V_i} + \frac{l_j}{V_j} + T_{FB} \tag{5.3}$$

From Figure 5.2, headway and dwell time for train *i* and *j*, when passing at *m* = 4, can be determined as follows:

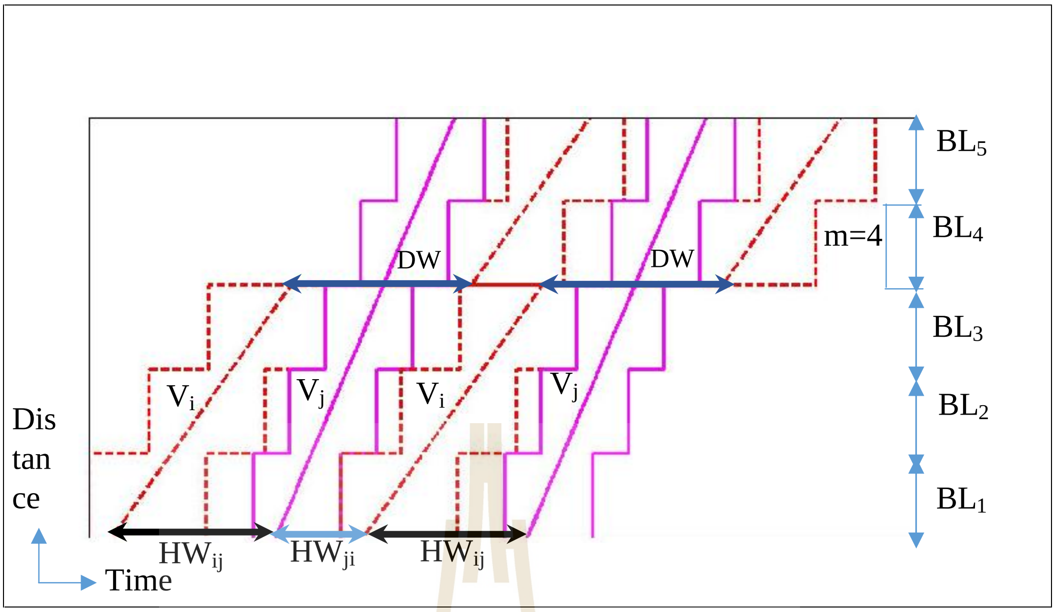

Figure 5.2 Time Space Diagram for Train *i* passing Train *j* in block 4

m=4

$$HW_{ij} = \frac{3BL + l_i}{V_i} - \frac{2BL + l_i}{Vj} + T_{FB} \tag{5.4}$$

$$DW_i = \frac{4BL + l_j}{V_j} - \frac{3BL}{V_i} + T_{FB} + HW_{ij} \tag{5.5}$$

$$HW_{ji} = \frac{BL + l_j}{V_j} + T_{FB} \tag{5.6}$$

From the time space diagram in Figure 5.1-5.2, it can be seen that when the leading train is slower (Vi<Vj), the following train will need to overtake the first one. The minimum headway between trains *i* and *j* under an equal block length section can be determined as in Equation (5.7). The minimum dwell time can be calculated as in Equation (5.8), regardless of the overtaking position.

$$HW_{ij} = \frac{BL(m-1)+l_i}{V_i} - \frac{BL(m-2)}{V_j} + T_{FB} \tag{5.7}$$

$$DW_i = \frac{2BL+l_j}{V_j} - \frac{l_i}{V_j} + 2T_{FB} \tag{5.8}$$

When two type of trains run alternately in a given section, the headway of the third train which follows the second train can be determined from the overtaking position to avoid conflict between the two trains. Two cases need to be considered; (1) when passing occurs before the midpoint (m-1< n/2), and (2) when passing occurs after the midpoint (m-1≥ n/2). In the first case HW_{ji} depends on relationship between total section length and the overtaking bock as shown in Equation (5.9).

$$HW_{ji} = \frac{BL(n-2m+2)}{V_i} + \frac{BL(2m-n-1)+l_j}{V_j} + T_{FB} \tag{5.9}$$

In the second case HW_j equals to blocking time of trains *j* as shown in Equation (5.10).

$$HW_{ji} = \frac{BL+l_j}{V_j} + T_{FB} \tag{5.10}$$

Where HW_{ij} =headway between trains i and j,

HW_{ji} =headway between trains i and j,

Vi =speed of train i,

Vj =speed of train j,

BL =block length,

N =number of blocks in the analysis section,

m =overtaking block

T_{FB} =signal watching time +clearing time in signal +clearing time in block +release time

5.4.2 Capacity Analysis

Capacity analysis takes into consideration the number of trains within the analysis period. In other words, the last train departs from the last block completely before time T (Abril et al., 2008). N example in Figure 5.3 shows two type of train, i and j, running alternately where Vi < Vj in one hour. Trains of type i complete 6 trips and type j 6 trips. The capacity on this 5-block section is 6+6=12 trips. The capacity can be determined as shown in Equation (5.11).

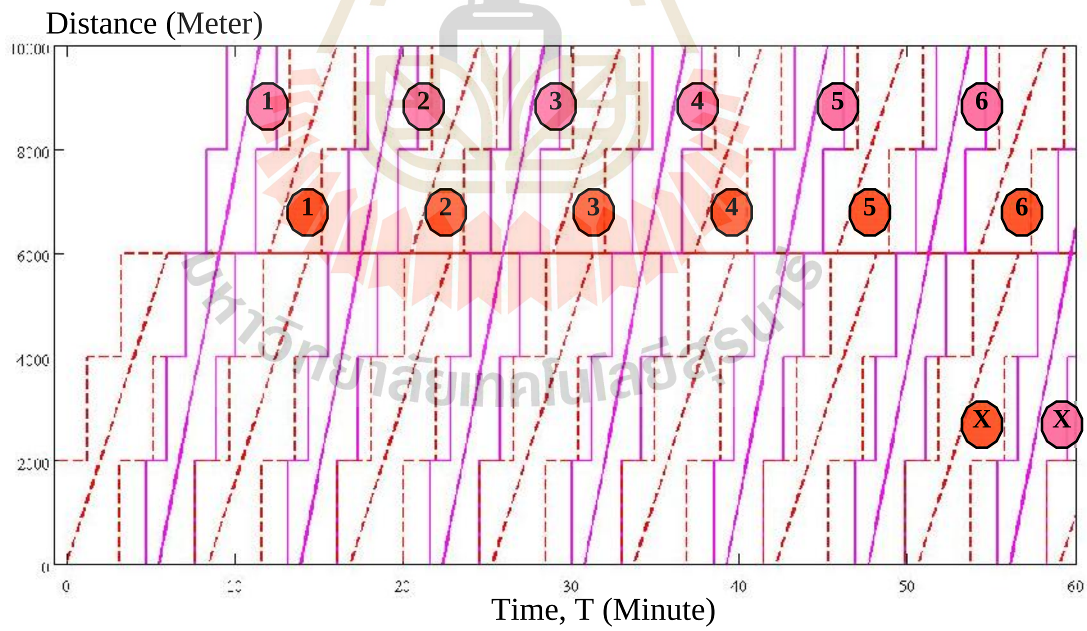

Figure 5.3 Consideration of trains which complete the trips within analysis period.

When Vi<Vj and passing occurs at block m, the capacity can be determined as

$$C = \frac{T - \dfrac{BL(n) + l_i}{V_i} - T_{FB} - DW_i}{HW_{ij} + HW_{ji}} + 1 + \frac{T - \dfrac{BL(n) + l_j}{V_j} - T_{FB} - HW_{ij}}{HW_{ij} + HW_{ji}} + 1 \quad (5.11)$$

Where

HW_{ij} = Headway between the first train of type i and the second train of type j

HW_{ji} = Headway between the second train of type j and the third train of type i,

DW = dwell time of train of type i waiting for train of type j to pass,

C = Line capacity

5.5 RESULTS AND DISCUSSION

The research results should be presented clearly and right to the point with accompanying figures and tables. These figures and tables should be referred to in the content. Explanation must not repeat what is already given in the content.

The study concludes that scheduling faster train to overtake slower one at any point of the section always reduce the minimum headway and increase capacity. Further conclusions can be drawn as follows:

5.5.1 Passing and Capacity

Scheduling fast trains to overtake slow ones increases line capacity. For example, consider train i with speed Vi = 60 km/hr leading train j with speed Vj = 100 km/hr in a 5 -block section. Figure 5.4 show that capacity increase when dwell time of the slow trains i is extended to allow trains j to pass.

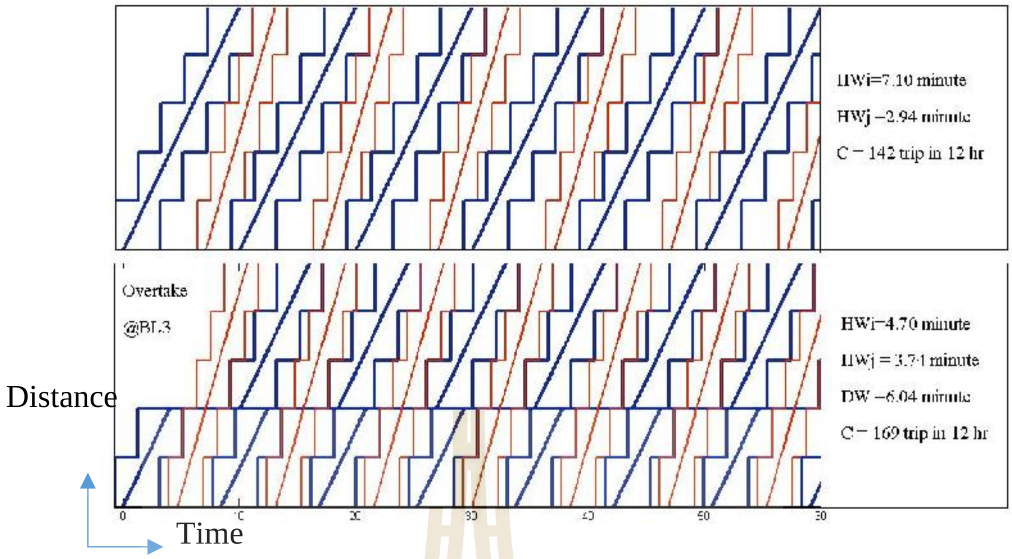

Figure 5.4 Comparison between following train and passing train schedules

5.5.2 Overtaking position and Capacity

Capacity changes with the overtaking position. The overtaking position may be any block from the second to the nth. Capacity is identical between two symmetrical overtaking positions from both ends. For example, passing at block m = 3 and m = n-2, or m =4 and m = n - 3, will result in the same capacity value. The capacity increases when overtaking block is located near the midpoint, and is lower as the distance is farther away from it. The overtaking points near the beginning and the end of the section yields the lowest capacity, which is still higher than the following-train case. For example, Figure 5.5 show two leading and following trains running at 60 and 100 km/hr. When the second train passes the first at the 4th block the network achieve the highest capacity. This holds true regardless of speed difference.

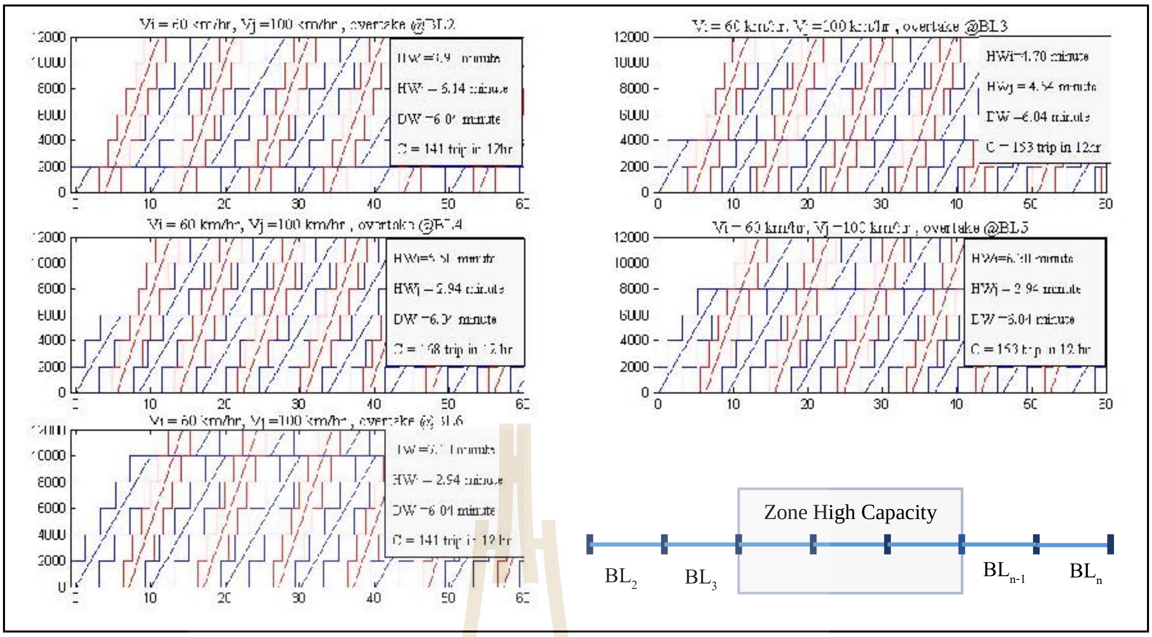

Figure 5.5 Train diagram showing effects of overtaking position to capacity

5.5.3 Number of blocks and capacity

The analysis of number of blocks in the section versus capacity uses the analytical equations as given above. It is finds that, in case of leading is slower than the following one, the best overtaking position is at (n/2)+1 with even number of blocks as shown in Figure 5.6 and at (n+1)/2 and (n+3)/2 with odd number of block as shown in Figure 5.7.

In addition to overtaking position, block length also affect the capacity. If the block lengths are long the capacity is low (Dicembre & Ricci, 2011). Shortening block length increases capacity and directly reduce dwell time.

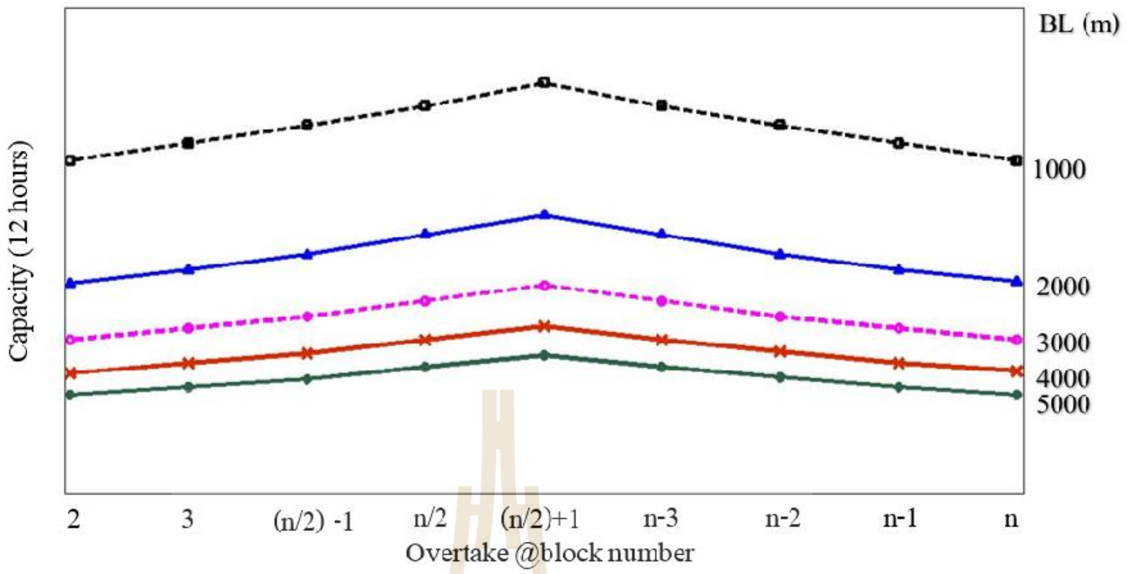

Figure 5.6 Capacity on the section with even number of blocks

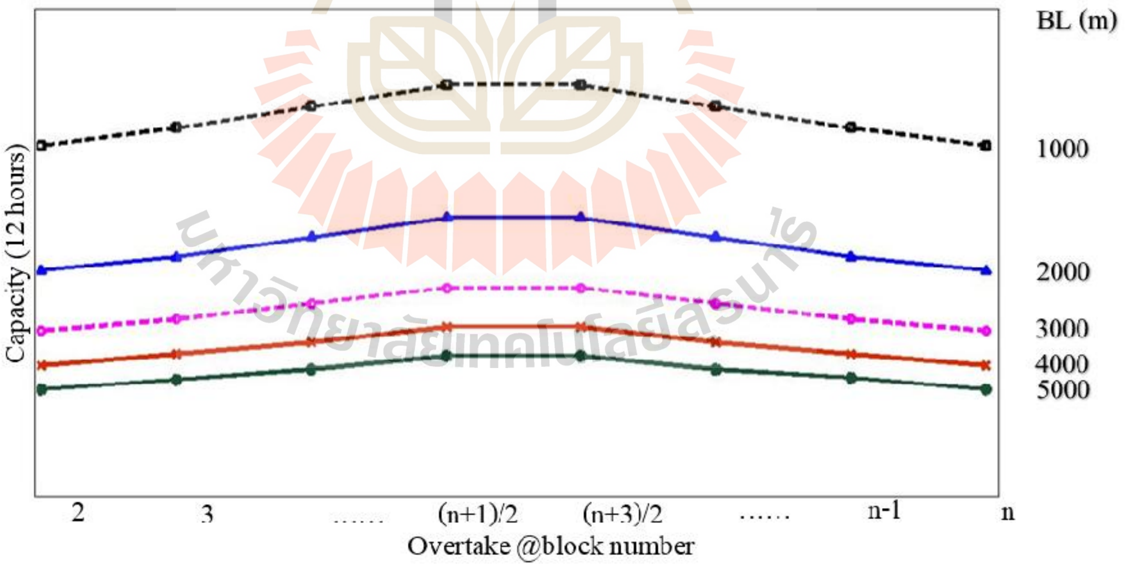

Figure 5.7 Capacity on the section with odd number of blocks

5.5.4 Speed and Capacity

Speed difference of the trains also affects capacity. The highest capacity is achieved when the same type of trains run together. The larger the speed difference, the lower the capacity. The high speed rail do not always yield high capacity, especially if it has to be operated on the same network with low speed ones. Heterogeneity of the trains greatly reduce the lone capacity in both following and passing schemes. Figure 8 shows the first train with speed of 60 km/hr is released and the flowing train passes at the optimum position where the highest capacity is achieved. The following train running at 75 km/hr would result in higher capacity than those run with 100 km/hr. Although 100 km/hr train would be much faster, but it needs to keep large minimum headway due to safety reason.

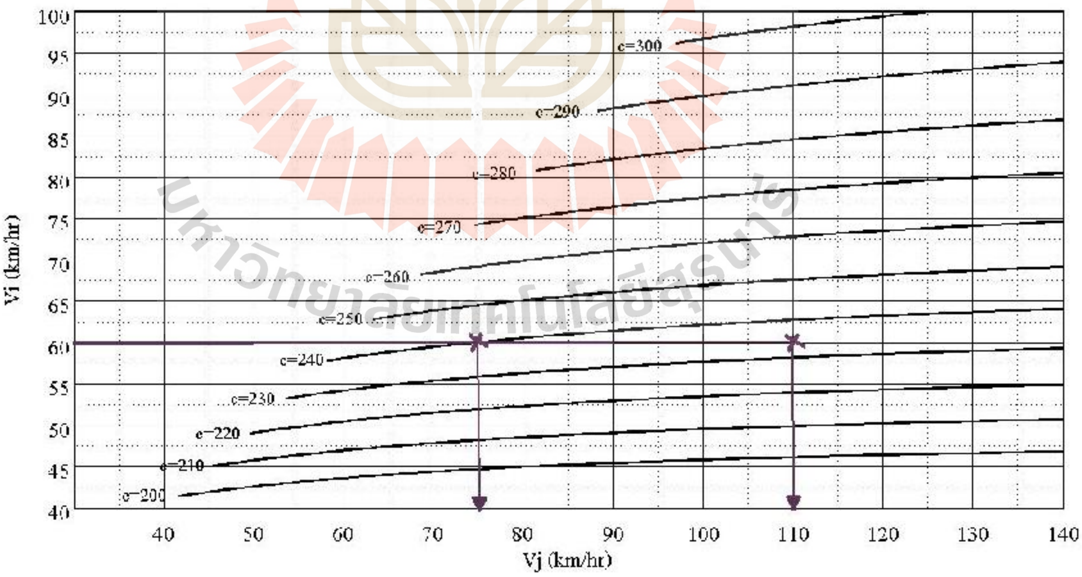

Figure 5.8 Relationship between speed difference and line capacity

Trains with speed higher than 140 km/hr may need longer block length to overcome stopping distance. Thus, this analysis did not consider such high speed operation.

5.6 CONCLUSIONS

Scheduling passing for trains with different speeds will improve the line capacity. On a section with equal block length, the only factor that determine the best overtaking position is the number of blocks. This position is not affected by speed nor block length.

Relationship between capacity and overtaking position is symmetrically linear. For example in the section with 6 blocks, overtaking position at 2nd or 6th block will result in the same capacity. As the trains only overtaking one another at the stations or sidings, the appropriate position to build these sidings should be the position that maximize the capacity (Higgins, Kozan, & Ferreira, 1997). The analysis suggests that when the number of block is an even number, the siding should be built at Block (n/2)+1. When the number of blocks is odd, the siding should be built at either block (n+1)/2 or block (n+3)/2. In addition to overtaking position, capacity also varies with the block length. The longer the block, the lower the capacity.

Speed difference affects minimum headway and minimum dwell time to let the other train pass. Trains with lower speed difference will result in higher capacity. High speed trains tend to lose capacity when running with very slow trains. The heterogeneous service consisting of express, rapid, local and freight trains should consider grouping trains with similar speed characteristics and assign appropriate overtaking block. Minimum headway should also be calculated to plan train release to enhance line capacity and best accommodate the passengers.

5.7 ACKNOWLEDGEMENTS

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CHAPTER VI

DEFINING THE OPTIMAL TRAIN OVERTAKING POSITION USING GENETIC ALGORITHM

6.1 ABSTRACT

This study focused on fixing low capacity problem when slow trains lead faster ones. The analysis was performed to reduced time headway and arrange train passing without conflict. The case study involved Thanon Chira Junction – Khon Kaen Section on the Northeastern Line for a total of 183.74 km and 27 blocks. The section contains unequal block lengths in which the optimum overtaking position could not be determined. Instead this research applied genetic algorithm to find the best solution under limitations on safe headway, dwell time constraints, and fixed block condition. It was found that Sala Din Station was the best location for overtaking. It would increase the line capacity up to 76 percent in comparison with non-passing operation. When the maximum block length was divided in halves, the best overtaking position shifted to Nong Bua Lai, and the capacity increased up to 79 percent. The increased capacity depended on section length and overtaking station.

6.2 INTRODUCTION

Currently many countries experience pollution problem (Ó Gallachóir, Howley et al. 2009; Ratanavaraha and Jomnonkwao 2015), energy crisis (Limanond, Jomnonkwao et al. 2011; Travesset-Baro, Gallachóir et al. 2016), and increase in private vehicles (Mohamad and Kiggundu 2007). Sustainable transportation have received attention and become the trend in setting national development policies and strategies. The main missions are to reduce CO2, reserve energy (Liu, Lund et al. 2013), promote alternative energy (Raslavičius, Keršys et al. 2014), encourage public transport use (Wang, Hokao et al. 2011) and to create mode shift from road and air to rail (Gangwar and Sharma 2014). Rail transportation is an environmental-friendly transportation mode which releases low greenhouse gases (Wang, Chen et al. 2015) and consume less energy per unit of freight and passenger transport compared with others. The Government of Thailand also gives priority to sustainable transportation and development. It accelerates a great number of rail transportation projects including 873-km double track for Northern, Northeastern and Southern lines. As a result, the State Railway of Thailand (SRT) expects its network capacity to increase significantly as many passing conflicts will be eliminated. This research analyzes double track operation on a 183.47 km section from Thanon Chira Junction to Khon Kaen Station. This section is divided into 27 blocks as shown in Figure 6.1

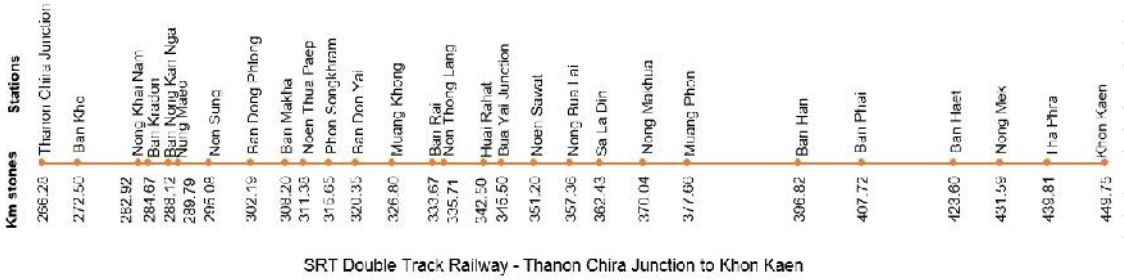

Figure 6.1 SRT Thanon Chira – Khon Kaen Double Track Railway

Railway capacity reflects the serviceability of the system which may not easily be measured. The capacity can be maximized by strategic train scheduling. Train schedule can be improved by several objective functions including minimizing expected total delay (Meng and Zhou 2011), minimizing passenger travel time (Corman, D’Ariano et al.), minimizing overall expenditure (Mišauskaite and Bagdonas 2006) and wait time (Wendler 2007), and optimizing total energy consumption and traversing time. The analysis usually too complicate to be solved by analytical methods. Yang et al (Yang, Li et al. 2012) applied genetic algorithm to seek network-based optimal strategies. Zhan and Kroon used mixed integer programming model to minimize the total weight train delay and the number of cancelled trains for one directional operation (Zhan, Kroon et al. 2015). D’Ariano proposed a model to solve the scheduling problem with an alternative graph formulation (D’Ariano, Pacciarelli et al. 2007). Optimization based framework for the evaluation of railway timetables (Corman, D’Ariano et al. 2014) and optimization based algorithms (Mu and Dessouky 2011) have also been applied to solve the scheduling problem. Scheduling for train passing is another technique to increase the line capacity. Salido and Barber proposed an algorithm which compare the dwell time and the minimum headway along with the angles that reflect relative speeds (Salido, Barber et al. 2012).

This research realizes the importance of sustainable transportation development to reduce pollution and environmental problems. It aims to improve train service focusing on following and passing operation, capacity evaluation and factor affecting capacity on an unequal block length section. It also investigate the optimal overtaking conditions to make the best use of existing and planned infrastructure.

6.3 METHODOLOGY

This research considered railway capacity on a future double track section of Thanon Chira Junction – Khon Kaen Station of Northeastern line. Capacity was presented as the maximum number of trains on the section which could be calculated from the reciprocal of the average headway between two successive trains. To maximize the capacity, one must minimize the headway. This study dealt with scheduling two types of trains with speeds vi and vj moving in the same direction. The minimum headway was calculated under given speed conditions, blocking time model (Pachl 2002; Landex and Kaas 2005; Medeossi, Longo et al. 2011; Büker 2013; de Fabris, Longo et al. 2014; Hansen. and Pachl. 2014; Fumasoli, Bruckmann et al. 2015), and fixed block rule which allows only one train per block to avoid conflict. Finally train passing scheme followed train priority rules (Chiang, Hau et al. 1998; Barber, Salido et al. 2004; Corman, D'Ariano et al. 2011; Kanai, Shiina et al. 2011; Dündar and Şahin 2013; Heydar, Petering et al. 2013; Krasemann 2015). The optimum overtaking position was the one which yielded the maximum capacity. The minimum time headway and dwell time were determined by blocking time stairways (Hansen. and Pachl. 2014) on a time-distance diagram. Genetic algorithm was applied to determine the best passing position.

6.4 FOLLOWING TRAIN ANALYSIS

Line capacity can be determined by $C = 1440/T_{min}$, where T min is the minimum time headway when two trains with speeds V_i and V_j run in the side direction. This study looks at the case where train i with speed V_i led train V_j with speed vj when $V_i < V_j$. Then T_{min} equals to the total headways $HW_{ij} + HW_{ji}$. The analysis of minimum headway can be illustrated in the flowchart of Figure 6.2 and can also be applied to other cases.

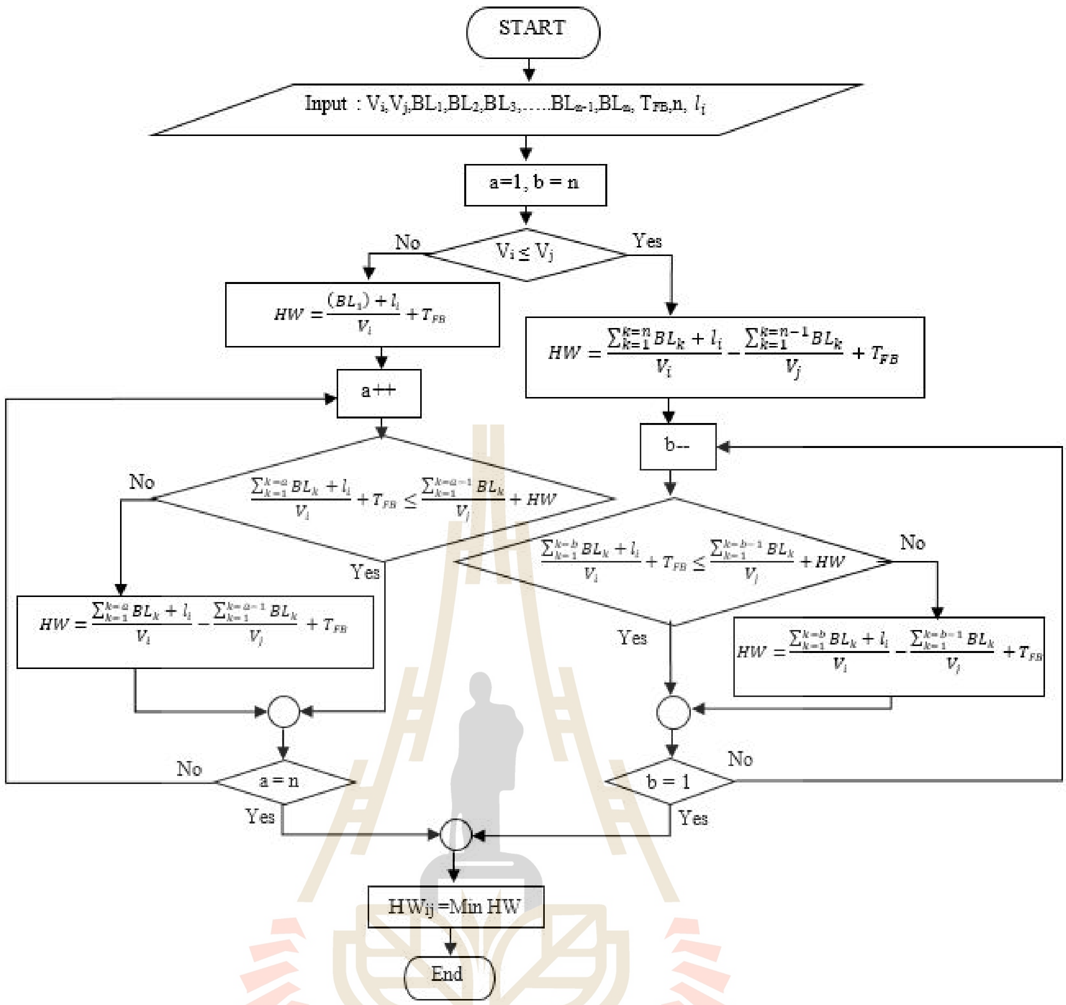

Figure 6.2 Headway Determination Diagram

Where HW_{ij} =headway between trains i and j,

HW_{ji} =headway between trains j and i,

V_i =speed of train i,

V_j =speed of train j,

l_i = length of train i,

BL_k =block length ที่ block k ,

n =number of blocks in the analysis section,

T_{FB} =clearing time in the block and signal

The analysis determined the minimum time headway in a fixed-block system for two trains traveling in the same direction with cruising speeds of V_i and V_j respectively (Heydar, Petering et al. 2013). Figure 6.3 shows trains with speed V_i and V_j running alternately in the section from Thanon Chira to Khon Kaen Station using time stairways on a time distance diagram as a visualization tool.

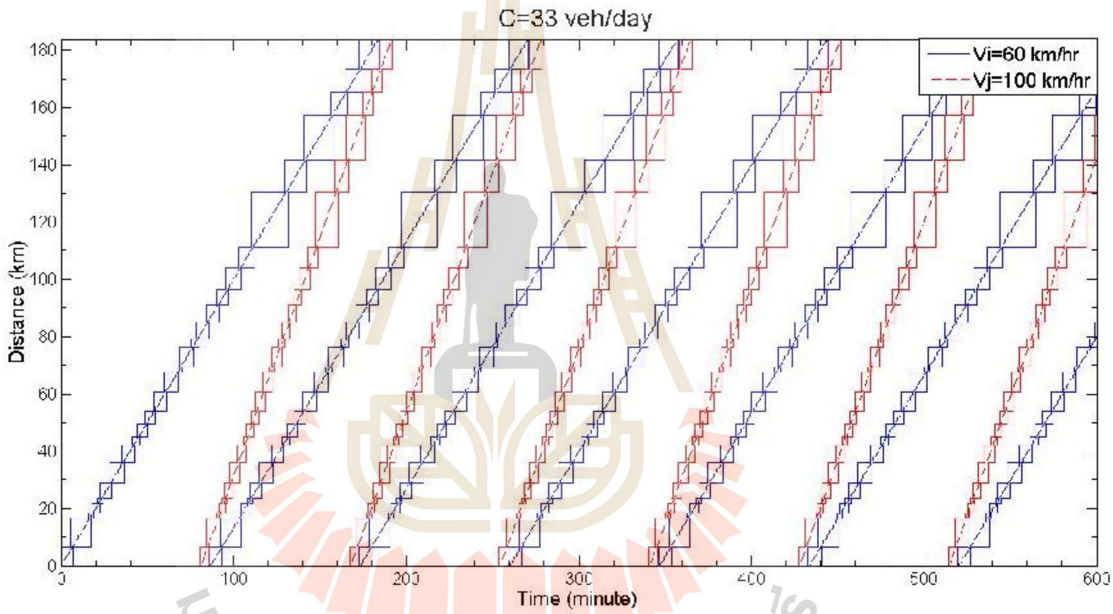

Figure 6.3 Time-space Diagram Showing Trains running with minimum time headway.

The time headway consists of running time, train clearance time, signal clearance time and block clearance time. Therefore the capacity on the section n with unequal block length is a function of several factors as follows:

$$C_{follow,unb} = f(BL_1, BL_2, BL_3, ...BL_n, n, V_i, V_j, l_i, l_j, T_{FB}) \tag{6.1}$$

Where B_{Ln} = length of block n

D_{OD} = total distance from the first to last stations,

BL_{OD} = sum of lengths of the first and the last blocks,

V_i and V_j = speeds of train i and j,

l_i and l_j = lengths of train i and j,

T_{FB} = time to clear signal and block.

The maximum number of trains per day can be determined from

$$C_{follow,eqb} = \frac{2880}{\frac{(\Delta v)D_{OD} + BL_{OD}(V_i)}{V_i V_j} + \frac{l_i}{V_i} + \frac{l_j}{V_j} + 2T_{FB}} + 2 \qquad (6.2)$$

Where $BL_{OD} = BL_1 + BL_n$, $D_{OD} = \sum_{k=1}^{k=n} BL_k$

6.5 PASSING TRAIN ANALYSIS

When a slow train leads a faster one, it requires a long headway to leave enough distance for the faster train not to run into the leading one. If passing is arranged with sufficient dwell time, a new and shorter headway can be determined with an optimal passing location that yields the maximum capacity.

The capacity of the passing scheme in an unequal block length section depends on block lengths, distance before and after passing, and trains speeds. Nonetheless, the critical block of time headway and dwell time change its position upon passing location. The analysis to determine the best passing location is too complex for close form solution. Hence, genetic algorithm (GA) is applied. The objective function is to maximize railway capacity under fixed block constraints as shown in Equation (6.3)

$$\text{Maximum} \qquad C_i^m + C_j^m \tag{6.3}$$

$$C_i^m = \frac{T - \dfrac{l_i + \sum_{k=1}^{k=n} BL_k}{v_i} - T_{FB} - d_{ij}^{\min,m}}{h_{ij}^{\min,m} + h_{ji}^{\min,m}} \tag{6.3.a}$$

$$C_j^m = \frac{T - \dfrac{\sum_{k=1}^{k=n} BL_k + l_j}{v_j} - T_{FB} - h_{ij}^{\min,m}}{h_{ij}^{\min,m} + h_{ji}^{\min,m}} \tag{6.3.b}$$

$C_i^m, C_j^m \geq 0$ And $C_i^m, C_j^m \in \text{int}$

Where

$h_{ij}^{\min,m}$ = minimum time headway between train i leading train j obtained from determination of critical block when passing at block m;

$h_{ji}^{\min,m}$ = minimum time headway between train j leading train i obtained from determination of critical block when passing at block m;

$d_{ij}^{\min,m}$ = minimum safe dwell time for train i when passing at block m;

C_i^m = number of trains i during time period T when passing at block m; and

C_j^m = number of trains j during time period T when passing at block m.

6.5.1 Safe Headway and Dwell Time Constraints

The safe headway and dwell time constraints check the conditions of $h_{ij}^{\min,m}$ $d_{ij}^{\min,m}$ and $h_{ji}^{\min,m}$,m when passing occurs at any given block m so that train i can stop for train j to pass without conflict throughout the section. Equations (6.4) to (6.7) enforce the safe time headway and dwell time constraints between pairs of trains.

Safe headway and dwell time constraints for GA analysis include the following:

$$hw_{ij}^{\min,m} \geq \frac{BL_x V_j - \Delta V \sum_{k=1}^{k=x-1} BL_k}{V_i V_j} + \frac{l_i}{V_i} + T_{FB} \quad ; 1 \leq x < m, x \in \text{int} \tag{6.4}$$

$$d_{ij}^{\min,m} \geq \frac{BL_y V_i - \Delta V \sum_{k=1}^{k=y-1} BL_k}{V_i V_j} + \frac{l_j}{V_j} + T_{FB} \quad ; m \leq y \leq n, y \in \text{int} \tag{6.5}$$

$$h_{ji}^{\min,m} \geq \frac{BL_{zb} V_i - \Delta V \sum_{k=1}^{k=zb-1} BL_k}{V_i V_j} + \frac{l_j}{V_j} + T_{FB} \quad ; 1 \leq zb < m, zb \in \text{int} \tag{6.6}$$

$$h_{ji}^{\min,m} \geq \frac{BL_{za} V_j - \Delta V \sum_{k=1}^{k=za-1} BL_k}{V_i V_j} + \frac{l_i}{V_i} + T_{FB} + d_{ij}^{\min,m} - 2h_{ji}^{\min,m} \quad ; m \leq za \leq n, za \in \text{int} \tag{6.7}$$

Where x is the block position that determines headway ij

y is the block position that determines dwell time

zb is the block position that determines headway ji

za is the block position that determines headway ji

6.5.2 Fixed Block Condition

The fixed block condition checks for safety when the faster train j passes train i at block m. Only one train can run in a block at any given time. Given that speeds for slow train 1 and 2 are V_{i1} and V_{i2}, and for fast train 1 and 2 are V_{j1} and V_{j2} respectively, the fixed block condition is checked before and after passing as shown in Figure 6.4.

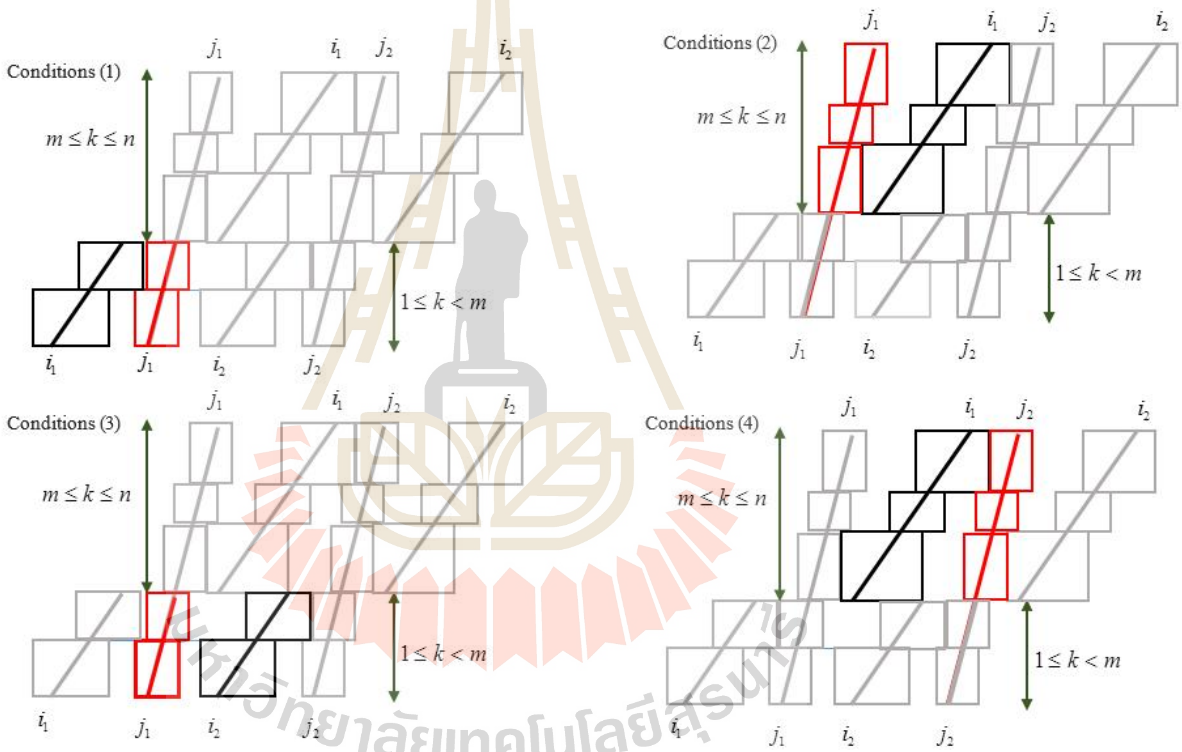

Figure 6.4 Fixed Block Condition Verification

Condition (1) checks for train i1 and train j1 before passing

$$\frac{\sum_{k=1}^{k=k-1} BL_k}{V_j} + h_{ij}^{\min,m} - \frac{\sum_{k=1}^{k=k} BL_k}{V_i} - \frac{l_i}{V_i} - T_{FB} \ge 0 \quad ; \ \forall k \in \text{int}, 1 \le k < m \tag{6.8}$$

Condition (2) checks for train j1 and train i1 after passing

$$\frac{\sum_{k=1}^{k=k-1} BL_k}{V_i} + d_{ij}^{\min,m} - \frac{\sum_{k=1}^{k=k} BL_k}{V_j} - \frac{l_j}{Vj} - T_{FB} - h_{ij}^{\min,m} \geq 0 \quad ; \ \forall k \in \text{int}, m \leq k \leq n \tag{6.9}$$

Condition (3) checks for train j1 and train i2 after passing

$$\frac{\sum_{k=1}^{k=k-1} BL_k}{V_i} + h_{ji}^{\min,m} - \frac{\sum_{k=1}^{k=k} BL_k}{V_j} - \frac{l_j}{V_j} - T_{FB} \geq 0 \qquad ; \ \forall k \in \text{int}, 1 \leq k < m$$

(6.10)

Condition (4) checks for train i1 and train j2 after passing

$$\frac{\sum_{k=1}^{k=k-1} BL_k}{V_j} + 2h_{ij}^{\min,m} + h_{ji}^{\min,m} - \frac{\sum_{k=1}^{k=k} BL_k}{V_i} - \frac{l_i}{V_i} - T_{FB} - d_{ij}^{\min,m} \geq 0 \quad ; \ \forall k \in \text{int}, m \leq k \leq n$$

(6.11)

6.5.3 Optimization Model

Optimization model are set with objective function and constraints as shown in (6.3) to (6.11). The analysis algorithm can be illustrated in Figure 6.5. A MATLAB-based program are used to seek for the answer. The results reveal the best overtaking locations in form of integer variable as shown in Figure 6.6. This set of command can be used for all routes and variables can be altered. The program running time will be longer as the number of blocks is increased because the conflict-free minimum headway and dwell time are sought for each passing location.

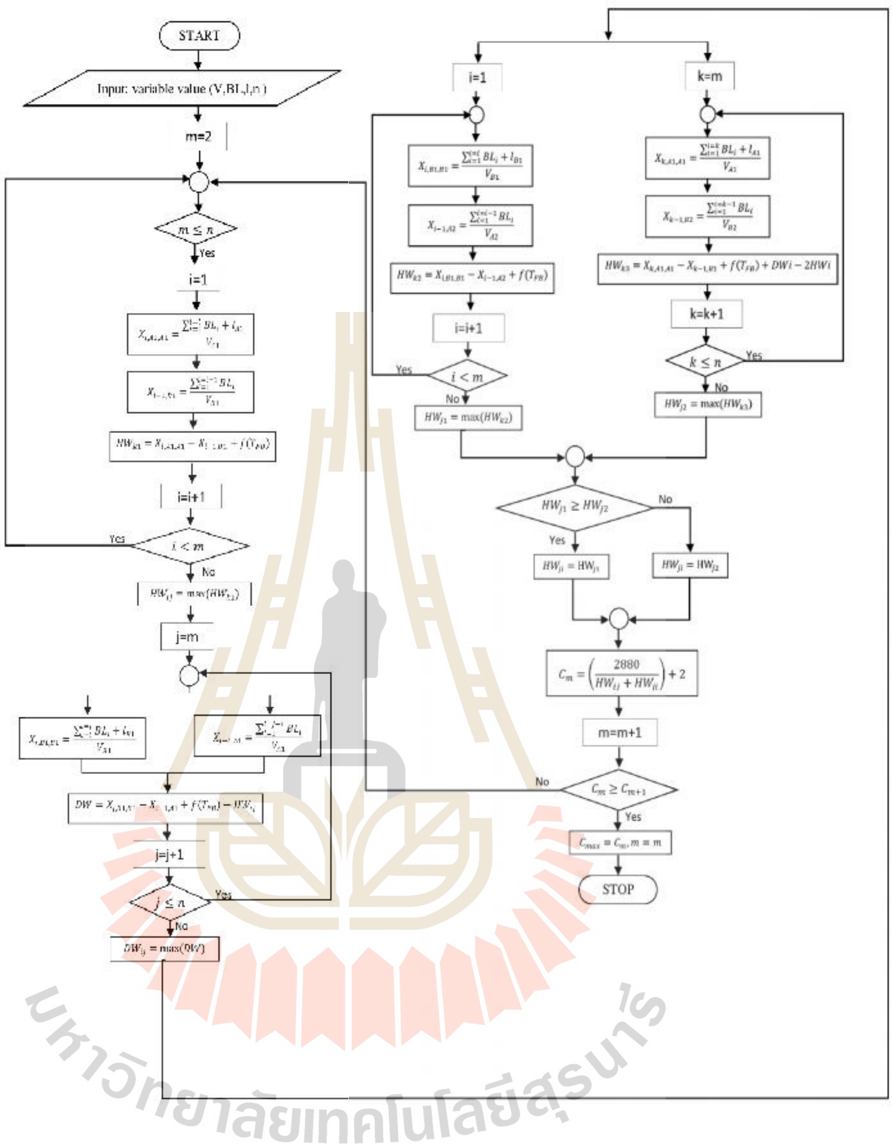

Figure 6.5 Flow chart for determining best overtaking position

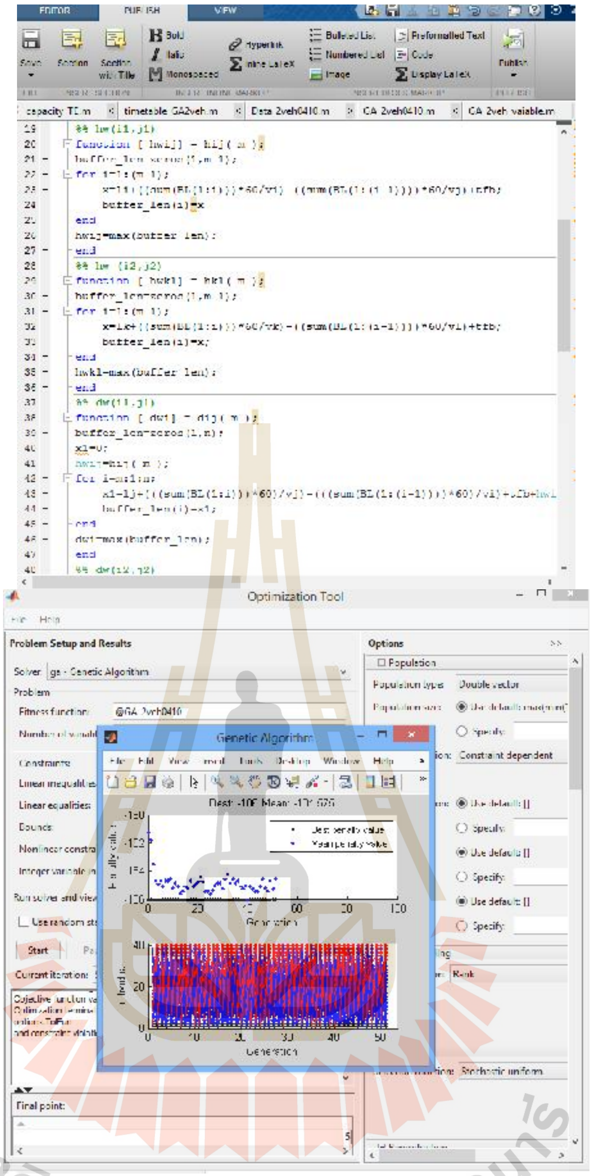

Figure 6.6 Optimal overtaking position analyzed by MATLAB program

The analysis for double track Thanon Chira – Khon Kaen section of the northeastern line found that the best overtaking position was always at Sala Din station (20^{th} block), regardless of speed difference. Figure 6.7 shows optimum overtaking position analysis under various speed differences.

Figure 6.8 shows a passing train scenario where V_i = 60 km/hr and V_j = 100 km/hr. Figure (6.8a) shows the case when passing at the best location (20th block) which yielded 58 trains/day. Figure (6.8b) shows the case when passing at the best location (17th and 23rd blocks) which yielded 61 trains/day. As it was known that block lengths affected capacity, a test was set where the critical block was divided into two. It was found that the capacity only increased by one train per day as shown in Figure (6.8c). Figure (6.8d) shows the case when passing occurs at two optimal locations. The best passing locations were Non Thong Lang (15th block) and Ban Phai (24th block). Such passing arrangement yielded only 66 trains/day.

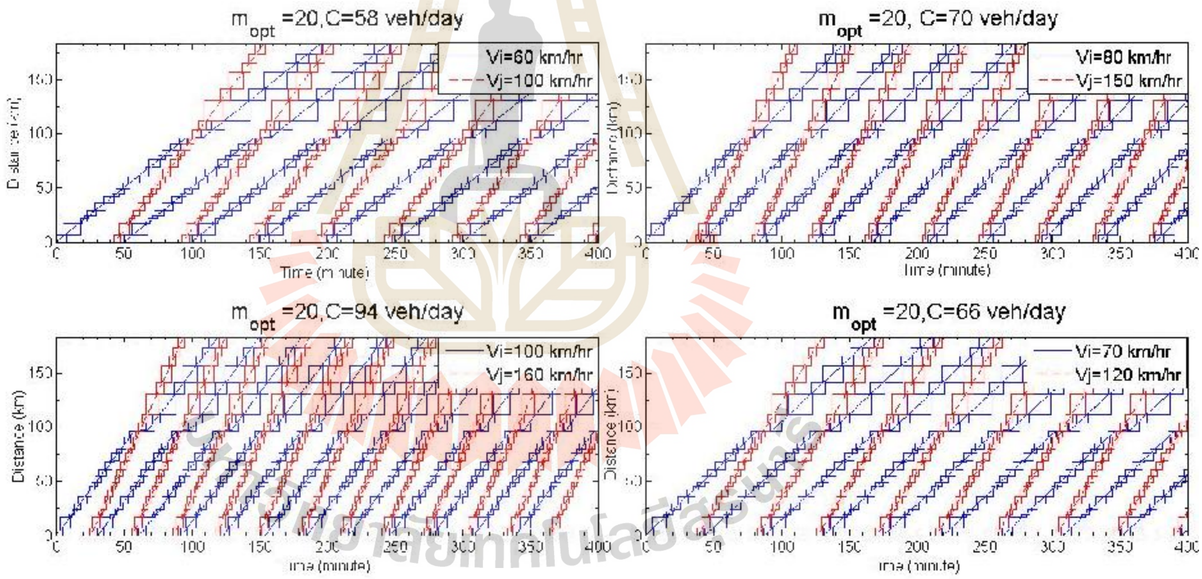

Figure 6.7 Train diagram showing optimal overtaking position VS speed difference

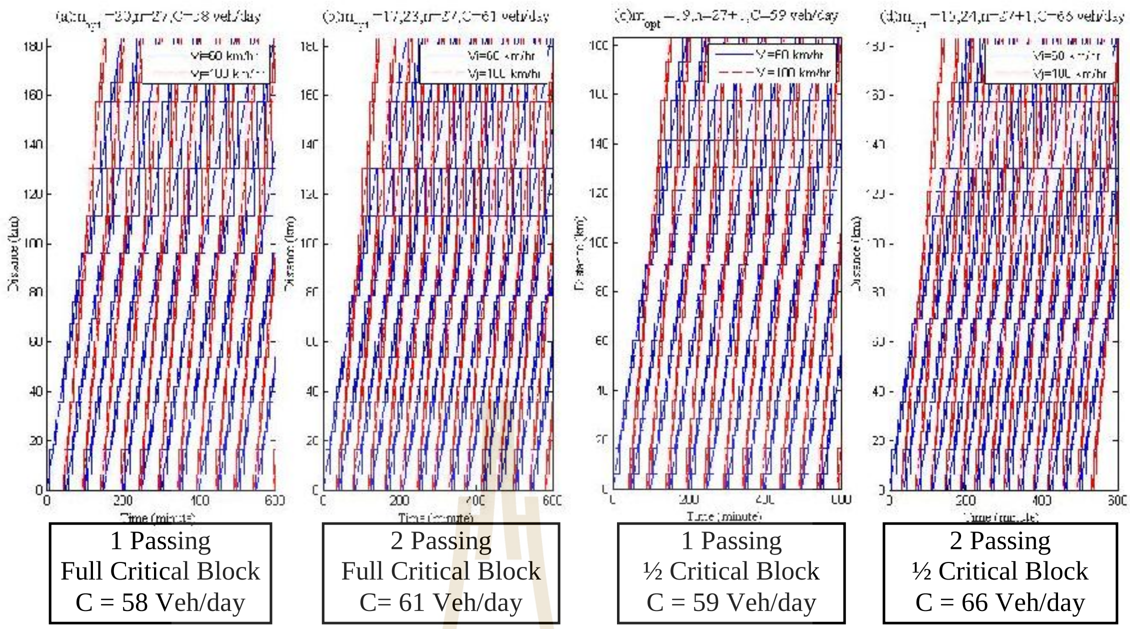

Figure 6.8 Train diagram showing optimal overtaking position VS capacity

6.6. DISCUSSION AND CONCLUSION

This research analyzed the effect of train scheduling to the line capacity using two types of trains with speed of V_i and V_j. When the trains follow one another, the capacity depended on the block length (BL), total distance (D_{OD}) the total length of the first and the last blocks, train speeds (V_i and V_j), speed difference (ΔV), train length (li and lj), and signal and block clearance time (T_{FB}). Trains operating at the same speed ($\Delta V = 0$) yielded the maximum capacity for the network. In reality, various types of trains shared the same track and run alternately to respond to market demand. In case a slow train led a faster one, the safe minimum time headway was long and deteriorated line capacity. Arranging for the faster train to pass would reduce time headway and increase capacity and operating efficiency.

The optimal overtaking position must be determined to maximize the line capacity. In unequal block length sections, the optimal overtaking position would depend on block length and the order of the blocks. The best overtaking position for a given section would be the same regardless of speed difference. The optimal overtaking position could not be determined by close-form mathematical model, but relied on genetic algorithm to find the best result. The problem was analyzed under a set of constraints including time headway, dwell time, and fixed block condition. The best overtaking position for Thanon Chira Junction – Khon Kaen Section was found at Saladin Station which increased capacity up to 76% from the non-passing scenario. Finally when the critical block was divided to two blocks, the best overtaking position changed to Nong Bua Lai (19^{th} Block) and the capacity increased by 79 % compared with the non-passing scenario. When passing two optimal locations, at Non Thong Lang and Ban Phai stations, capacity increased up to 100% from the non-passing scenario. The increased capacity also depended on distance. Overtaking in a longer section increased the capacity more than that in a shorter one under the same speed condition. Genetic algorithm helped finding optimal solution for overtaking position in a short time despite the complexity of the conditions.

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CHAPTER VII

CONCLUSION AND RECOMMENDATIONS

This research was conducted from the proposal for seeking the equation acquiring the capacity relevant to the actual train running providing the closer value than that of Scott's formula by analyzing minimum headway time under blocking time model which analyzed total time spent on running starting from signal and block clearing. The case studies were divided into equal and unequal block length route management both for the same direction and overtaking direction. Furthermore, the instrument was designed to simply figure out the answer of headway time by applying the design of Nomograph. There has been neither research on rail system conducted on this pattern nor the research on headway time under unequal blocking length analysis, and the suitable overtaking position consideration. This study was accomplished by dividing into four sections on the basis of research objectives including 1) to analyze critical block which determined minimum time headway of route, and the factors affecting route capacity 2) to design the instrument replacing the mathematic equation to figure out time headway 3) to study the analysis of time headway, dwell time, and suitable overtaking position consideration on equal block length, and 4) to analyze suitable overtaking position consideration on unequal block length by using genetic algorithm and estimating the increasing capacity as following details;

7.1 CRITICAL BLOCKS & MINIMUM HEADWAYS

According to the analysis of distance-time diagram of train running for equal block length routes when the two trains followed each other in the same direction in condition that the first train had higher speed than or equal speed as the second one (Vi >=Vj), it was found that the first train spent the time on the first block (T_{BL}), the second train could be allowable as the following train was slower so it could not overtake the first train. Thus, the first block would be Critical Block. In case that the first train run more slowly than the following train (Vi <Vj), the all involved blocks were needed to be considered in order not to be caught by the following train, Thus, the last block on the route was critical block.

For unequal block length routes, that the trains had equal speed during the longest block would determinate the headway between the trains according to Scott's formula. In case of different train speed, the longest block was not always critical block and there was no fixed formula for calculation but the consideration must be in sequence by using Algorithm in comparison to find the shortest headway. In other words, when the first train had faster speed than the following train, the first block route will be determined to be critical block and used to calculate for time headway and consider whether there was a conflict or not. If time headway originated from blocking time of the first block, it was firstly ordered min time headway. If not, it would be deferred to the position of conflict originality and consecutively analyzed until the last block of route without any conflict. In case that the first train was slower than the following train, the analysis had to be conducted from the last block recurring to the starting point.

The factors affecting train route capacity in the same direction on equal and unequal block length were block length, total distance, the total addition of the first block and the last block, the speed of both trains, the train length, and signal and block clearing time. The more different speed made the less capacity. Decreasing block length can increase capacity.

7.2. NOMOGRAPHS

From the design of Nomograph with the instruction python script in pynomo software for finding out the answer of time headway, touching graph of parallel coordinate system was used to replace mathematic equation to reduce the complicated analysis for minimum time headway. Especially, in the case that the trains did not run following each other on unequal block length route, the overlap of block use needed to be examined with repetitive loop. Thus, Nomograph design was accepted as an alternative instrument for rapidly finding the answer of time headway value to reduce the complicated analysis. The research which was designed according to the types of train speed to facilitate working was divided into three types including 1) the two trains having equal speed 2)the first train having less speed than the second train, and 3)the first train having more speed than the second train, under the involved variables which included train characteristic (train speed, train length) , infrastructure characteristic (distances, block length, number of block), and control system (signal-watching time, clearing time in signal , release time and clearing time in block). From the test of model Nomograph, it was found that the train could safely run after each other with time headway obtained from Nomograph without conflict point occurrence. Moreover, Nomograph for time headway could facilitate working by finding many answers in a variety of cases, having flexibility for continuous work application, and replacing equation analysis effectively.

7.3 OVERTAKING POSITION

For the management of fast trains overtaking slow trains on equal block length, the hypothesis determined that when the slow trains run before the fast train with safe minimum time headway until they were overtaken at any block m starting at the second block to n. At the overtaking position, the slow trains would wait equal the minimum dwell time when the slow trains could run after the fast trains without any crash until the last block. The minimum time headway at any overtaking position m would equal the difference of the time of the two trains leaving at the starting point until the block before overtaking (m-1) added to blocking time of fast trains during one block and minimum dwell time would equal the total time that the two trains used to clear signals, blocks, trains, and the time the trains spent on the second block of overtaking trains.

The relation between capacity and overtaking position is symmetrical. The overtaking position acquiring maximum capacity would be in block zone at the middle of routes and the increasing capacity would reduce according to the headway of overtaking position when linked to the middle point. From the study, it was found that the appropriate overtaking position on the route was at (n/2) +1 on even number block route, at (n+1)/2 on odd number block route, and (n+3)/2 when n was the number of Blocks. The factor of speed did not affect the appropriate overtaking position when running train was managed under minimum time headway, and minimum dwell time

7.4 GENETIC ALGORITHM

This research was the analysis of appropriate overtaking position on unequal block length route by using instruction function of genetic algorithms in MATLAB program to investigate the overtaking position with maximum capacity under the limitation of headway, dwell time constraints and fixed block condition which were determined to protect conflict occurrence throughout the route. The obtained answer would acknowledge what was the appropriate m overtaking position. The analysis found that the appropriate overtaking position was the relation between block length and the order of block on route. The appropriate overtaking position was still at the same position on route even if how much train speed was changed but it was changed from the former appropriate overtaking position due to the route change.

The best overtaking position for Thanon Chira Junction – Khon Kaen Section was found at Saladin (Block 20) Station which increased capacity up to 76% from the non-passing scenario. The percent of increasing capacity depended on the distance. The algorithm used for checking the condition for finding answers could also apply to use for other routes in building suitable overtaking path or managing train running for more route capacity.

7.5 RECOMMENDATIONS

This research analyzed time headway on the basis of blocking time model from the function of period of time the train used for running in the block with speed v, clear the train length *l* with speed v in the pattern of train running in the same direction. There are available points to be additionally studied in the future. Thus, researchers have conclusion to suggest interested people to continue further studies for the development of effective train running management. The analysis of time used for traveling from one station to another station should be conducted with the consideration on the travel time starting from accelerating engine until it had stable speed and decelerating the train. The study of train running in opposite direction should be also conducted. When the fast train runs after the slow train, there can be overtaking position before stopping instead of only using stable speed for analysis to arrange more effective train running schedules as well as the addition of train running patterns. Besides the study of many suitable overtaking patterns or many times of overtaking, checking the efficiency of time headway analysis, testing effectiveness of Time headway analysis obtained from the study should be compared to the test of simulation model.

The increasing capacity is possible on the route can be made by arranging the trains having close speed for less ΔV, the reduction of block length, arrangement of fast train overtaking slow train to decrease minimum time headway. All of three accomplishments could help increase the capacity of lines but the determination of maximum capacity train arrangement will depend on the service demand. Furthermore, the efficiency of management control is train's punctuality since nowadays the trains always face the problem of delay. Furthermore, if their infrastructures are improved and newly adapted, they potentially make the trains run on time. Consequently, the effort to adjust the train schedule for maximum capacity as presented earlier can achieve the goal more effectively.

APPENDIX A

LIST OF PUBLICATIONS

List of Publications

Determining critical line blocks and minimum train headways for equal and unequalblock lengths and various train speed scenarios (ENGINEERING JOURNAL - Accepted)

Analysis and design of Nomographs for minimum headway calculation (SONGKLANAKARIN JOURNAL OF SCIENCE AND TECHNOLOGY – Accepted)

Analysis of appropriate overtaking position under equal block lengths (LOWLAND TECHNOLOGY INTERNATIONAL– Under review)

BIOGRAPHY

Mrs. Onanong Sangphong was born on 23 January 1984 at Nonsung District Nakhon Ratchasima. She started her elementary school at Bankaoangkaew School and her secondary school at Nongplub Vithaya School. She graduated from Suranaree University of Technology with a bachelor's degree in Engineering (Transportation Engineering) in 2006. After that, she worked for Bangkok Chonlakit Company Limited in the position of Transport operation officer. Then, she returned to study for a master's degree and a doctor's degree at the same university.

At present, she is a lecturer of Construction Technology Program, Faculty of Industrial Technology, Nakhon Ratchasima Rajabhat University. Her interest is in transportation research including railway management system, transportation planning, and logistics.